

University of Nebraska - Lincoln

**DigitalCommons@University of Nebraska - Lincoln**

---

USDA Forest Service / UNL Faculty Publications

U.S. Department of Agriculture: Forest Service --  
National Agroforestry Center

---

2016

# Ecosystem Services of Woody Crop Production Systems

Ronald S. Zalesny Jr.

*USDA Forest Service, [rzalesny@fs.fed.us](mailto:rzalesny@fs.fed.us)*

John A. Stanturf

*USDA Forest Service*

Emile S. Gardiner

*USDA Forest Service*

James H. Perdue

*USDA Forest Service*

Timothy M. Young

*University of Tennessee*

*See next page for additional authors*

Follow this and additional works at: <http://digitalcommons.unl.edu/usdafsfacpub>



Part of the [Forest Biology Commons](#), [Forest Management Commons](#), [Other Forestry and Forest Sciences Commons](#), and the [Plant Sciences Commons](#)

---

Zalesny, Ronald S. Jr.; Stanturf, John A.; Gardiner, Emile S.; Perdue, James H.; Young, Timothy M.; Coyle, David R.; Headlee, William L.; Bañuelos, Gary S.; and Hass, Amir, "Ecosystem Services of Woody Crop Production Systems" (2016). *USDA Forest Service / UNL Faculty Publications*. 335.

<http://digitalcommons.unl.edu/usdafsfacpub/335>

This Article is brought to you for free and open access by the U.S. Department of Agriculture: Forest Service -- National Agroforestry Center at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in USDA Forest Service / UNL Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

---

**Authors**

Ronald S. Zalesny Jr., John A. Stanturf, Emile S. Gardiner, James H. Perdue, Timothy M. Young, David R. Coyle, William L. Headlee, Gary S. Bañuelos, and Amir Hass

# Ecosystem Services of Woody Crop Production Systems

Ronald S. Zalesny Jr.<sup>1</sup> · John A. Stanturf<sup>2</sup> · Emile S. Gardiner<sup>3</sup> · James H. Perdue<sup>4</sup> · Timothy M. Young<sup>5</sup> · David R. Coyle<sup>6,7</sup> · William L. Headlee<sup>8,9</sup> · Gary S. Bañuelos<sup>10</sup> · Amir Hass<sup>11</sup>

Published online: 28 April 2016

© Springer Science+Business Media New York (outside the USA) 2016

This document is a U.S. government work and is not subject to copyright in the United States.

**Abstract** Short-rotation woody crops are an integral component of regional and national energy portfolios, as well as providing essential ecosystem services such as biomass supplies, carbon sinks, clean water, and healthy soils. We review recent USDA Forest Service Research and Development efforts from the USDA Biomass Research Centers on the provisioning of these ecosystem services from woody crop production systems. For biomass, we highlight productivity and yield potential, pest susceptibility, and bioenergy siting applications. We describe carbon storage in aboveground woody biomass and studies assessing the provision of clean and plentiful water. Soil protection and wildlife habitat are also mentioned, in the context of converting lands from traditional row-crop agriculture to woody production systems.

**Keywords** Biomass · Carbon · *Eucalyptus* · *Pinus* · *Populus* · Provisioning services · Regulating services · *Salix* · Soils · Water

## Abbreviations

$\delta^{13}\text{C}$	Leaf carbon isotope composition
3-PG	Physiological Principles Predicting Growth model
AHA	Auburn Harvest Analyzer
BioSAT	Biomass Site Assessment Tools
DBH	Diameter at breast height
FIA	USDA Forest Service Forest Inventory and Analysis
FRCS	USDA Forest Service Fuel Reduction Simulator
GIS	Geographic information system
LAI	Leaf area index
MAV	Mississippi Alluvial Valley
MSW	Municipal solid waste
OPEC	Organization of the Petroleum Exporting Countries
SRIC	Short-rotation intensive culture

**Electronic supplementary material** The online version of this article (doi:10.1007/s12155-016-9737-z) contains supplementary material, which is available to authorized users.

✉ Ronald S. Zalesny, Jr  
rzalesny@fs.fed.us

<sup>1</sup> USDA Forest Service, Northern Research Station, Institute for Applied Ecosystem Studies, Rhinelander, WI, USA

<sup>2</sup> USDA Forest Service, Southern Research Station, Center for Forest Disturbance Science, Athens, GA, USA

<sup>3</sup> USDA Forest Service, Southern Research Station, Center for Bottomland Hardwoods Research, Stoneville, MS, USA

<sup>4</sup> USDA Forest Service, Southern Research Station, Forest Products Center, Knoxville, TN, USA

<sup>5</sup> Forest Products Center, University of Tennessee, Knoxville, TN, USA

<sup>6</sup> D.B. Wamell School of Forestry and Natural Resources, University of Georgia, Athens, GA, USA

<sup>7</sup> Southern Regional Extension Forestry, Athens, GA, USA

<sup>8</sup> Division of Agriculture, Arkansas Forest Resources Center, University of Arkansas, Monticello, AR, USA

<sup>9</sup> School of Forestry and Natural Resources, University of Arkansas at Monticello, Monticello, AR, USA

<sup>10</sup> USDA Agricultural Research Service, Water Management Research Unit, Parlier, CA, USA

<sup>11</sup> Agricultural and Environmental Research Station, West Virginia State University, Institute, WV, USA

SRWC	Short-rotation woody crops
USDA ARS	USDA Agricultural Research Service
USDA FS	USDA Forest Service
USDA FS R&D	USDA Forest Service Research and Development
USDA NASS	USDA National Agriculture Statistics Service
WUE	Water use efficiency
ZCTA	ZIP Code Tabulation Area

## Introduction

Prior to the Industrial Revolution, most societies depended on trees for energy as well as other uses (e.g., building materials, fodder, and medicinals). Wood was the primary energy source in the USA for both residential (fuelwood) and industrial (charcoal) purposes until the mid-nineteenth century [1]. As late as 1900, wood provided 21 % of energy consumption, but declined to 5 % by 1950 [2]. The Organization of the Petroleum Exporting Countries (OPEC) Oil Embargo of 1973–1974 caused a resurgence of interest in bioenergy from wood. A Society of American Foresters Task Force Report [3] estimated that dedicating 10 % of the arable private land in the USA to bioenergy plantations would add 4.5 quads (i.e., quadrillion BTUs) of energy to US production (estimated at 75 quads in 1976), with the potential to increase to 8.3 quads if new technology was used [4]. Since that time, the annual US primary energy consumption has increased to 98.5 quads in 2014, with 4.8 quads (i.e., ~5 % of the total energy consumption) coming from renewable biomass [5]. According to the baseline scenario of the US Billion-Ton Update [6], at US\$60 per dry ton, energy crops [which include short-rotation woody crops (SRWC) as well as perennial grasses and annual energy crops] will have the potential to contribute 400 million dry tons of biomass (i.e., ~37 % of total) in 2030. This potential increases to a range of 540–799 million dry tons of biomass (i.e., ~39–49 % of total) under the high-yield scenario, which assumes a 2–4 % annual increase in yield.

One advantage of woody biomass for bioenergy is that it can be produced on land marginal or unsuitable for commercial agriculture; thus, it does not compete for land with food crops. By one estimate, there are more than 2.0 million ha of marginal land in the northeastern USA alone, thought to be suitable mostly for willow (*Salix* spp.) [7]. In the Southeast, econometric models of the potential of genetically modified freeze-tolerant rose gum (*Eucalyptus grandis* Hill ex Maiden) × Timor mountain gum (*Eucalyptus urophylla* S.T. Blake) predicted an expansion of up to 1.1 million ha of *Eucalyptus* plantations, replacing pine plantations and naturally regenerated pine stands [8]. An assessment of lands suitable for purpose-grown, short-rotation hybrid poplars (*Populus* species and their hybrids, excluding the aspens) showed that

0.4 million ha were potentially available in Wisconsin and Minnesota, representing nearly one third (i.e., 31 %) of the land base across these states [9].

## USDA Forest Service Biomass Research

The use of fast-growing forest tree species to produce biomass for fuel, fodder, and building materials has a long history. For example, Dickmann [10] traced the development of SRWC from coppice systems in antiquity to the beginnings of structured genetic improvement with poplars in the early twentieth century. Research programs on SRWC began in the 1960s; 50 years ago, the concept of silage sycamore (*Platanus* sp.) was conceived in Georgia [11, 12]. The basic premise was to grow woody crops in a fashion similar to agronomic crops, with close spacing (1000–35,000 stems ha<sup>-1</sup>) and short rotation cycles (1, 2, or 3 years). A series of hardwood plantations was established, beginning in 1966 on a variety of sites. The objectives were to screen species for differences in productivity and to evaluate different spacings and rotation lengths [13]. Although the original systems were impractical for most hardwood species [12], an even more densely planted system termed woodgrass was proposed in the late 1970s for hybrid poplar [14] and shrub willow [15], the latter of which is still used today. The concept of short-rotation intensive culture (SRIC) spread to other regions, spurred by the OPEC Oil Embargo of 1973–1974. Many species, both hardwoods and softwoods, have been investigated for bioenergy, fiber, timber production, or some combination (Table 1). Two growth characteristics, however, have dominated species choices and favored hardwoods: rapid initial stem growth and coppicing ability. However, certain species' demand for specific site requirements has worked against many hardwoods.

Three locations were instrumental for advancing USDA Forest Service (USDA FS) research into biomass and bioenergy: Stoneville, MS (33.42°N, 90.90°W); Rhinelander, WI (45.64°N, 89.47°W); and Lehigh Acres, FL (26.67°N, 81.81°W). Researchers at these three locations and others cooperated with university and industry colleagues on breeding, testing, growing, harvesting, and processing (Fig. 1 and ESM Online Resource 1). While others have been tested, *Populus* has been the most popular taxon for research on SRWC [21] (Table 2). *Populus* spp. have been widely studied and planted operationally because of their rapid juvenile growth, ease of hybridization, and vegetative propagation [68, 69]. Researchers at the Stoneville and Rhinelander locations have been intimately involved in developing material and systems for SRWC. Research on eucalypts for pulpwood, begun in 1959 by the Florida Forests Foundation, was the origin of the research program begun in 1968 by the USDA FS and the Florida Division of Forestry at Lehigh Acres [70].

**Table 1** Species considered promising for short-rotation woody crop production systems in the USA (adapted from [16, 17, 18, 19])

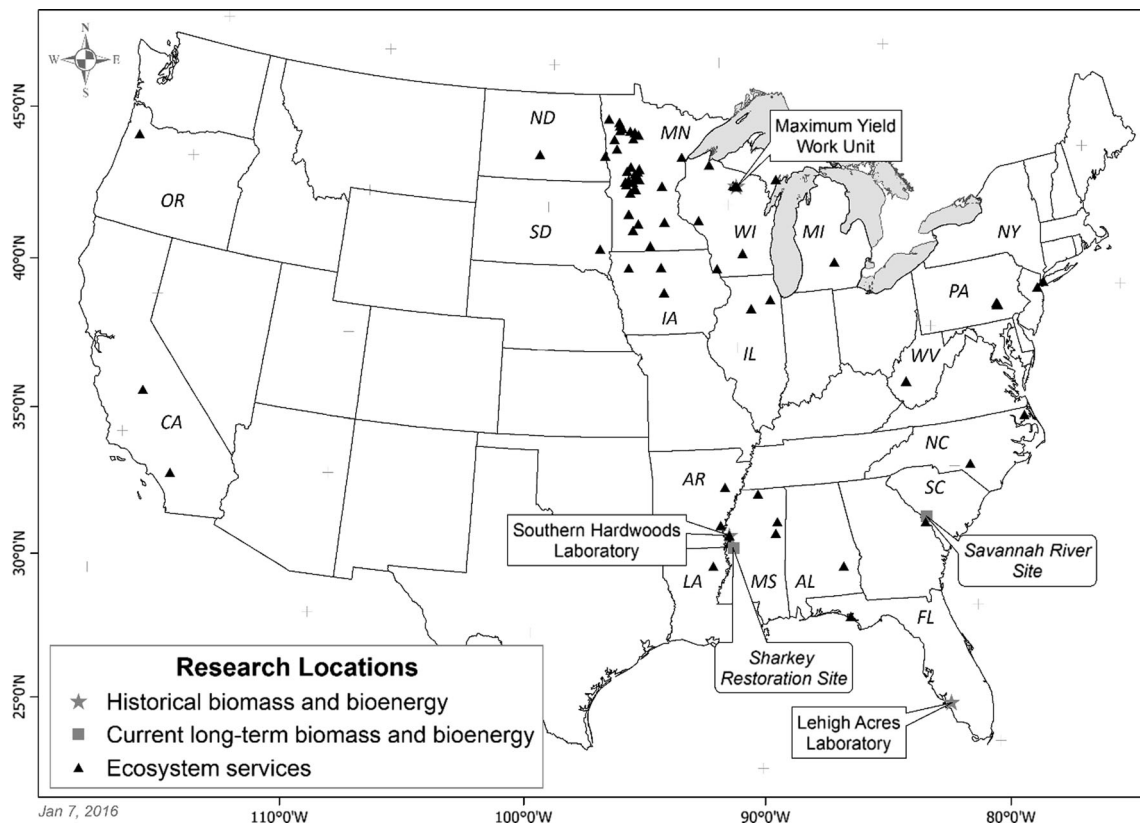
Species	Common name	Region							
		NW	W/SW	GP	LS	MW	S/SE	NE	SB/T
<i>Acer saccharinum</i> L.	Silver maple			X				X	
<i>Ailanthus altissima</i> (Mill.) Swingle	Tree of heaven				X				
<i>Falcataria moluccana</i> (Miq.) Barneby & Grimes (formerly <i>Albizia falcataria</i> )	Peacocksplume								X
<i>Alnus glutinosa</i> (L.) Gaertn.	European alder					X			
<i>Alnus rubra</i> Bong.	Red alder	X							
<i>Atriplex canescens</i> (Pursh) Nutt.	Four-wing saltbush		X						
<i>Elaeagnus umbellata</i> Thunb.	Autumn olive					X			
<i>Eucalyptus amplifolia</i> Naudin	Cabbage gum						X		X
<i>Eucalyptus dorrigoensis</i> (Blakely) L.A.S. Johnson & K.D. Hill (syn. <i>Eucalyptus benthamii</i> )	Camden white gum						X		
<i>Eucalyptus camaldulensis</i> Dehnh.	River red gum								X
<i>Corymbia citriodora</i> (Hook.) K.D. Hill & L.A.S. Johnson (syn. <i>Eucalyptus citriodora</i> )	Lemon-scented gum								X
<i>Eucalyptus dalrympleana</i> Maiden	Mountain white gum								X
<i>Eucalyptus globulus</i> Labill.	Tasmanian blue gum								X
<i>Eucalyptus grandis</i> W. Hill ex Maid.	Grand eucalyptus								X
<i>Eucalyptus macarthurii</i> H. Deane & Maiden	Camden woollybutt								X
<i>Eucalyptus robusta</i> Sm.	Swamp mahogany						X		
<i>Eucalyptus saligna</i> Sm.	Sydney blue gum								X
<i>Eucalyptus sideroxylon</i> A. Cunn. ex Woolls	Red ironbark								X
<i>Eucalyptus viminalis</i> Labill.	Manna gum								X
<i>Eucalyptus grandis</i> × <i>Eucalyptus urophylla</i> <sup>a</sup>	Hybrid eucalypt						X		X
<i>Liquidambar styraciflua</i> L.	Sweetgum						X		
<i>Pinus banksiana</i> L.	Jack pine				X				
<i>Pinus clausa</i> (Chapm. ex Engelm.) Vasey ex Sarg.	Sand pine						X		
<i>Pinus elliottii</i> Engelm.	Slash pine						X		
<i>Pinus nigra</i> × <i>Pinus densiflora</i>	Hybrid pine				X				
<i>Pinus sylvestris</i> L.	Scots pine				X				
<i>Pinus taeda</i> L.	Loblolly pine						X		
<i>Platanus occidentalis</i> L.	American sycamore						X		
<i>Populus deltoides</i> Bartr. ex Marsh.	Eastern cottonwood					X	X		
<i>Populus</i> hybrids	Hybrid cottonwood	X				X			
<i>Populus</i> hybrids	Hybrid aspen				X				
<i>Populus</i> hybrids	Hybrid poplar	X			X			X	
<i>Populus tremuloides</i> Michx.	Quaking aspen				X				
<i>Populus balsamifera</i> L. subsp. <i>trichocarpa</i> (Torr. & A. Gray ex Hook.) Brayshaw	Black cottonwood	X							
<i>Prosopis alba</i> Griseb.	Mesquite		X						
<i>Robinia pseudoacacia</i> L.	Black locust			X		X		X	
<i>Salix</i> spp.	Willow spp.				X				
<i>Triadica sebifera</i> (L.) Small (syn. <i>Sapium sebiferum</i> )	Chinese tallow						X		
<i>Tamarix</i> L.	Tamarisk		X						
<i>Ulmus pumila</i> L.	Siberian elm			X					

NW Northwest, W/SW West/Southwest, GP Great Plains, LS Lake States, MW Midwest, S/SE South/Southeast, NE Northeast, SB/T Subtropics/Tropics

<sup>a</sup> Genetically engineered for cold tolerance or lignin biosynthesis [20]

The SRWC focus at the USDA FS Southern Hardwoods Laboratory in Stoneville, MS, has been the native eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.). An early

evaluation of hybrid poplar was conducted in cooperation with the Oxford Paper Company [71], but generally, hybrids have not done as well in the Deep South as the native eastern



**Fig. 1** Map of research sites for ecosystem services of woody crop production systems in the USA. The three sites indicated in *rectangular boxes (with square edges)* are historic locations for USDA Forest Service

woody crop biomass research and development. The two sites indicated in the *remaining two boxes (with round edges)* are current, long-term biomass and bioenergy research locations

cottonwood, in part due to greater susceptibility to *Septoria* stem canker [68]. Early work on poplar breeding in the South was done at Stoneville during the 1950s [72]. Phenotypically superior trees were selected, clonally propagated, tested, and released [73]. The clonal cottonwood selections released by researchers at Stoneville, taken from native populations growing along the Mississippi River and rivers elsewhere in the Southern USA, are the foundation of poplar breeding programs around the world [68, 74]. Of the 14 superior clones described by Mohn et al. [74], five of these were given a “blue tag” certification (i.e., highest level) in 1974. This was the first blue tag certification of any forest reproductive material in the USA [75]. Observations of cottonwood growing in natural stands provided the information needed to specify the basic requirements for establishing and growing cottonwood, but until 1960 only pilot tests were established [76]. Working with cooperators, a flexible system of *Populus* culture was developed [77], and in 1960, industrial plantings were initiated by Crown Zellerbach Corporation with the purchase of a 6070-ha cattle and cotton plantation near Fitler, MS, that was developed into a cottonwood plantation. Other companies in the region followed suit [76].

The Maximum Yield Work Unit was established at the USDA FS Northern Institute of Forest Genetics in

Rhineland, WI, in 1971. The work unit took a systems approach, with researchers from different disciplines, to select promising species, investigate establishment methods for SRWC culture, and evaluate pulping qualities and the economic viability [78]. More basic research was incorporated in 1976 and furthered by funding from the US Department of Energy from 1977 to 2002. Poplars are prone to hybridizing, and *P. deltoides* introduced to Europe by botanists spontaneously crossed with the native black poplar (*Populus nigra* L.) and came to be known as Canadian poplars (*Populus × canadensis* Moench). These wild Euro-American hybrids stimulated interest in producing controlled crosses. The first documented controlled cross of western black poplar (*Populus trichocarpa* Torr. & Gray) and *P. deltoides* in 1924 led to vegetative propagation of selected clones, and by the 1930s, poplar breeding programs were widespread in Europe and North America [10]. Researchers at Rhineland have concentrated on hybrid poplars for SRWC [79], although they have also investigated other species including jack pine (*Pinus banksiana* Lamb.), larch [*Larix laricina* (Du Roi) K. Koch], alder (*Alnus* spp. Mill.), and green ash (*Fraxinus pennsylvanica* Marshall) [78].

The history of *Eucalyptus* in the continental USA dates back to the California Gold Rush of the mid-1800s [70], but



**Table 2** Short-rotation woody crop genomic groups and genotypes tested for the provision of ecosystem services and development of environmental technologies in the United States

Genus/genomic group	Genotype(s)	Reference(s)
<b><i>Populus</i></b>		
<i>P. deltoides</i>	91.05.02, 91.08.09, 110531, 110804, 112127, 112830, 5910100, 7300500, 7300501, 7300502, 7302801, 7302810, 8000104, 8000105, 3-1, 14-71, 14-129, 32-5, 42-7, 51-5, 61-2, 61-4, 61-8, 62-4, 63-1, 66-9, 72C-2, 79-4, 90-3, 92-4, 93-6, 94-4, 100-3, 115-1, 119-6, 147-1, 171-1, 180-1, 189-4, 192-2, 193-5, 220-5, 252-4, 42-7, 51-2, C910401, C910502, C910506, C910508, C910510, C910613, C910706, C910809, C910903, C912500, C916000, C916001, C916013, C916021, C916101, C916201, C916304, C916305, C916306, C916323, C916325, C916400, C916401, C916413, C916500, C917900, C918001, C918012, CHILI.2-01, CHILI.2-02, D1, D3, D5, D7, D9, D10, D11, D101, D102, D103, D104, D105, D106, D107, D108, D109, D110, D111, D112, D113, D114, D117, D118, D119, D120, D121, D122, D123, D124, D125, D126, D129, D130, D132, D133, D134, D135, D137, D139, D141, D144, D147, Kentucky 8, M2-9, M3-4, M7-3, Ohio Red, S7C1, S7C8, S7C15, S13C20, ST66, ST70, ST71, ST72, ST75, ST109, ST260, ST261, ST264, WV99, WV316, WV415, WV416, wild-type collections	[22–43]
<i>P. grandidentata</i>	Wild-type collections	[42]
<i>P. suaveolens</i> subsp. <i>maximowiczii</i>	897-1, 898-1, 900-2, 904-2, 1050-10, 1051-4, 1051-10, 77331, 77341, 77441	[41]
<i>P. nigra</i>	13-17, 13-308, 22SNOP01, 21SNOP12	[22, 23, 40]
<i>P. trichocarpa</i>	062, 065, 072, 322, 12-106, 91-568, 93-968	[40, 44]
<i>P. deltoides</i> × <i>P. deltoides</i>	119.16, 11428.03, 12111911, 80X00601, 80X00603, 80X00605, 80X01015, 80X01038, 80X01059, 80X01107, 80X01109, 80X01110, 80X01112, 80X01132, 91X01-02, 91X02-01, 91X02-02, 91X04-01, 91X04-02, 91X04-04, 91X04-05, C9425R3, C9425R5, C9425S11, GB123602, GB250205, ISU.25-4, ISU.25-12, ISU.25-21, ISU.25-35, ISU.25-R2, ISU.25-R4, ISU.25-R5, WV94	[22, 23, 25, 26, 34, 41–43]
<i>P. deltoides</i> × <i>P. nigra</i>	13-366, 13-818, 13-822, 14-66, 117.53, DN5, DN17, DN21, DN31, DN34 (aka Eugenei), DN70, DN182, I45-51, NE222, OP367, PL-1, Simplot Alkaline, Tassman	[22–26, 34, 36, 40, 43, 45–53]
<i>P. deltoides</i> × <i>P. suaveolens</i> subsp. <i>maximowiczii</i>	25, 113.64, 202.37, 313.23, 313.55, DM101, DM105, DM113, DM115, Eridano, MWH2, MWH3, MWH5, MWH7, MWH10, MWH11, MWH12, MWH13, MWH14, MWH15, MWH17, NC14103, NC14104, NC14105, NC14106, NC14107	[22, 23, 25, 26, 34, 39, 40, 44, 54]
<i>P. nigra</i> × <i>P. suaveolens</i> subsp. <i>maximowiczii</i>	NM2, NM6	[22–26, 34, 36, 47]
<i>P. alba</i> × <i>P. alba</i>	12XAA9005, 8XAA9004	[22, 23]
<i>P. alba</i> × <i>P. grandidentata</i>	Crandon	[22–24, 55]
<i>P. alba</i> × ( <i>P. alba</i> × <i>P. grandidentata</i> )	11XAAG9102	[22, 23]
<i>P. trichocarpa</i> × <i>P. deltoides</i>	15-29, 23-91, 23-96, 24-305, 49-177, 50-197, 50-194, 52-225, 52-229, 184-40, 184-402, 184-408, 184-411, 195-529, 272-97	[25, 26, 34, 40, 49, 50, 53]
( <i>P. trichocarpa</i> × <i>P. deltoides</i> ) × <i>P. deltoides</i>	NC13377, NC13446, NC13451, NC13460, NC13475, NC13544, NC13548, NC13552, NC13559, NC13563, NC13568, NC13570, NC13608, NC13609, NC13624, NC13649, NC13652, NC13661, NC13668, NC13670, NC13672, NC13680, NC13684, NC13685, NC13686, NC13724, NC13747, NC13749, NC13800, NC13801, NC13807, NC13845, NC13850, NC13857, NC13863, NC13992, NC13999, NC14002, NC14015, NC14018, NC14042	[22–24, 36, 39, 44, 51, 56]
( <i>P. trichocarpa</i> × <i>P. deltoides</i> ) × <i>P. suaveolens</i> subsp. <i>maximowiczii</i>	233-3, 289-69	[40]
( <i>P. trichocarpa</i> × <i>P. deltoides</i> ) × <i>P. nigra</i>	345-1, 346-12, 347-13, 347-13, 347-14	[40]
<i>P. trichocarpa</i> × <i>P. suaveolens</i> subsp. <i>maximowiczii</i>	262-4, 272-98, 272-239, 281-181, 282-139, 286-74	[40]
<i>P. suaveolens</i> subsp. <i>maximowiczii</i> × <i>P. trichocarpa</i>	NE41	[43]

**Table 2** (continued)

Genus/genomic group	Genotype(s)	Reference(s)
<i>P. trichocarpa</i> × <i>P. nigra</i>	302-1, 302-4, 302-5, 302-6, 303-11, 303-12, 303-13, 303-14, 304-21, 304-22, 304-23, 304-24, 304-25, 304-26, 304-27, 304-28, 305-31, 305-32, 305-33, 305-34, 305-35, 306-41, 306-42, 306-43, 306-44, 306-45, 306-46, 306-47, 306-49, 306-52, 306-448, 307-51, 308-61, 309-71, 309-72, 310-84, 310-85, 310-87, 311-93, 312-101, 313-111, 313-112, 313-113, 313-114, 313-115, 314-121, 314-122, 314-123, 314-124, 315-131, 315-132, 315-134, 315-135, 315-136, 315-137, 316-141, 316-142, 316-143, 317-152, 317-153, 317-154, 318-161, 318-162, 318-164, 345-1	[25, 26, 34, 40]
<i>P. trichocarpa</i> × <i>P. trichocarpa</i>	D-01	[53]
<i>P. trichocarpa</i> × ( <i>P. trichocarpa</i> × <i>P. deltoides</i> )	353-273	[40]
<i>P. charkowiensis</i> × <i>P. cv incrassata</i>	NE308	[43]
<b>Salix</b>		
<i>S. dasyclados</i>	SV1	[42]
<i>S. eriocephala</i>	9837-77, S25, S287, wild-type collections	[42, 57]
<i>S. eriocephala</i> × <i>S. eriocephala</i>	S566	[57]
<i>S. interior</i>	Wild-type collections	[58–60]
<i>S. miyabeana</i>	SX64	[42]
<i>S. nigra</i>	Wild-type collections	[42, 58–63]
<i>S. purpurea</i>	94003, 94012	[57]
<i>S. sachalinensis</i>	SX61	[57]
<b>Pinus</b>		
<i>P. taeda</i>	7-56	[27–30, 64, 65]
<b>Platanus</b>		
<i>P. occidentalis</i>	Control-pollinated families	[27–31, 66, 67]
<b>Liquidambar</b>		
<i>L. styraciflua</i>	Control-pollinated families	[27–31]

Sections (in bold) and authorities for the aforementioned *Populus* species are: **Aigeiros** Duby—*P. charkowiensis* R. I. Schrod., *P. deltoides* Bartr. ex Marsh., *P. incrassata* Dode, *P. nigra* L.; **Tacamahaca** Spach—*P. suaveolens* Fischer subsp. *maximowiczii* A. Henry, *P. trichocarpa* Torr. & Gray; **Populus** L.—*P. alba* L., *P. grandidentata* Michx

Authorities for the remaining genera and species include: **Salix**—*S. dasyclados* Wimm., *S. eriocephala* Michx., *S. interior* Rowlee, *S. miyabeana* Seemen., *S. nigra* Marsh., *S. purpurea* L., *S. sachalinensis* F. Schmidt; **Pinus taeda** L.; **Platanus occidentalis** L.; **Liquidambar styraciflua** L.

eucalypts fell out of favor by the turn of the century. Interest spiked again from 1950 to 1970 and USDA FS research in California and Hawaii continued into the 1990s [80–82]. A sustained interest developed in the Southern USA, specifically in Florida [70, 83]. Industry-funded cooperative research programs provided support for the USDA FS Lehigh Acres Laboratory [84]. From 1965 to 1984, USDA FS researchers tested the best of 156 seed sources of 76 eucalypts for southern Florida, resulting in more than 1500 selected clones of *E. grandis* [85]. Swamp mahogany (*Eucalyptus robusta* Sm.), river red gum (*Eucalyptus camaldulensis* Dehnh.), and forest red gum (*Eucalyptus tereticornis* Sm.) were also selected and received lesser levels of genetic improvement [70, 84]. Commercial plantations persist today in southern Florida and Hawaii [21, 85]. In the past, deployment of *Eucalyptus* in the South north of lower Florida has been limited by severe freezes [70]. Nevertheless, a renewed search has begun for

freeze-tolerant species and provenances [86], as well as development of transgenic *E. grandis* × *E. urophylla* [8, 20].

Recently, a group of forest industry experts in the south-eastern USA were asked what hardwood species were best suited for biomass production [87]. They agreed that sweetgum (*Liquidambar styraciflua* L.) had broad regional application, although they acknowledged its relatively low growth rates. Frost-tolerant *Eucalyptus* spp. were recommended for the coastal zone, and poplar (*P. deltoides* and hybrids) was particularly favorable if cultivars tolerant of marginal site conditions became available. While acknowledging the potential for several hardwoods, the forest industry experts recommended considering loblolly pine (*Pinus taeda* L.) for SRWC. The proven capabilities of southern pines to sustainably produce biomass and a well-developed supply chain, particularly for plantation loblolly pine, certainly support the consideration of southern pine for SRWC [21, 88, 89]. Loblolly pine



does not readily sprout; hence, coppice rotations are infeasible. Because there are substantial markets for larger roundwood, biomass systems for loblolly pine can be flexible, running the gamut from dedicated single-product stands for bioenergy [90], dual-cropping for bioenergy and conventional products [91, 92], or intercropping pine with perennial energy grasses [93].

Over 50 years of intensive research and experimentation in the USA and globally has validated the basic premises of SRWC: use of species with rapid (indeterminate) initial stem growth and coppicing ability, in dense plantings, with short clear-felling cycles. In large part due to USDA FS Research and Development (USDA FS R&D), intensive cultural techniques have been developed, including genetically superior material, weed control, fertilization, and irrigation strategies [10, 88]. Optimizing cultural practices that match genetics to site and regulate density and rotation length to achieve greater leaf area maximize yield [78]. Advances in genetic and physiological biotechnology have opened the door to a new world of possibilities for tree growth and wood properties [10, 88]. Realization of these possibilities will be determined by regulatory constraints, public attitudes, and, of course, markets.

While historical efforts for the development of SRWC focused on the production of biomass for bioenergy, biofuels, and bioproducts, much of the more recent work has expanded to include broader objectives of achieving multiple ecosystem services. Specifically, USDA FS research conducted across the USDA Biomass Research Centers has utilized baseline information from these former studies to further develop and refine woody crop production systems for biomass production, carbon sequestration, water quality and quantity, and soil health. In addition, current systems have been expanded beyond traditional fiber production to other environmental technologies that incorporate SRWC as vital components for phytoremediation, urban afforestation, forest restoration, and mine reclamation (see [94] in this special issue).

## Ecosystem Services

The Millennium Ecosystem Assessment [95] categorizes ecosystem services into four groups. *Provisioning services* are the goods and products obtained from ecosystems (e.g., biomass, freshwater), while *regulating services* include the benefits obtained from an ecosystem's control of natural processes (e.g., carbon sequestration, soil quality). The four specific ecosystem services listed are highlighted below with respect to recent USDA FS research conducted at the USDA Biomass Research Centers. For biomass, we describe productivity potential and realized yields, as well as growth impacts from pests. The section ends with a discussion about the development of bioenergy siting applications. For carbon, regional implications are discussed, followed by a section highlighting

water quality and quantity across genera. The final ecosystem services section describes research on soils and wildlife habitat. Although it is beyond the scope of this paper, the remaining two groups include *cultural services* which are the non-material benefits obtained from ecosystems (e.g., spiritual and educational values) and *supporting services* that include the natural processes that maintain the other ecosystem services (e.g., nitrogen and water cycles) [95].

## Biomass

### Productivity Potential

#### Hybrid Poplar

Typical hybrid poplar productivity potential in the North Central USA has ranged from 4.0 to 13.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup>, with some values exceeding 20.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup> when matching genotypes to specific adaptation zones [22, 45]. The most common method for estimating hybrid poplar productivity has been to develop biomass equations based on simple traits such as diameter at breast height (DBH) and/or height [96, 97]. Others have developed more complex equations using additional allometric characteristics and wood properties [98]. While these equations have been useful and accurate when used only for the specific genotype or genomic groups they were developed for, even the seemingly more complex equations have not been robust enough to account for the broad amount of genetic variability among *Populus* species and their hybrids. More specifically, an equation developed for one clone is likely not adequate for other genotypes, especially those belonging to different species and taxonomic sections.

Recent work at the Central-Eastern and Northern-East Regional USDA Biomass Research Centers has included the development of biomass equations based on harvests of 198 hybrid poplar trees from two different regional testing networks [23, 46] that were established between the years 1987 and 2001 at 15 sites across the North Central USA (Fig. 1). Analyses are still ongoing, yet two initial trends are apparent. First, older equations commonly used in the region are not well suited for estimating biomass of newer genotypes, with previous equations consistently overestimating biomass productivity potential. Second, equations specific to genomic groups were sufficient for estimating biomass of the newer genotypes, with clone-specific equations resulting in minimal improvements in model fit compared to group-specific equations [99]. Hence, using group-specific equations was shown to be robust enough for the newer genotypes.

Nevertheless, recognizing limitations in robustness and complexity associated with biomass productivity equations, USDA FS scientists partnered with researchers from

Iowa State University to parameterize, calibrate, and validate the Physiological Principles Predicting Growth (3-PG) process-based growth model for hybrid poplars in the North Central USA [45]. While others have validated the model for loblolly pine and eucalypts [100] and poplars [101], this was the first validation for hybrid poplar in the USA. The aforementioned limitations are important to understand because biomass is largely driven by the response of genetic and physiological mechanisms controlling growth to site conditions such as climate and soils. Unlike biomass productivity equations, estimates from 3-PG are substantially more accurate given that the model accounts for differences in these genotype- and location-specific characteristics. More specifically, 3-PG uses solar radiation and temperature data along with species-specific photosynthetic parameters to establish maximum potential productivity, from which actual productivity is estimated based on limiting factors such as site fertility and water availability (as influenced by precipitation, soil water holding capacity, water table access, etc.) and allocated among tree components (stems, foliage, and roots) based on allometric relationships. Thus, productivity is estimated based on the site-specific availability of key resources and the species-specific physiological processes which govern the conversion of these resources into biomass. Based on this model development, estimates of hybrid poplar productivity were developed for Minnesota and Wisconsin [45]. The mean annual productivity ranged from 4.4 to 13.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup>, and the highest productivity potential was located in South Central Minnesota and southern Wisconsin. Productivity values decreased at higher latitudes.

These productivity modeling efforts were then further expanded with the development of an approach for deploying hybrid poplar production systems to increase yield and associated ecosystem services across the landscape [9]. Specifically, building on SRWC research dating back to the Maximum Yield Work Unit described above, knowledge of poplar silviculture was merged with large-scale spatial analyses to predefine zones of potential hybrid poplar adaptation that were ecologically sustainable [24] and economically feasible [102] across the landscape. Across both states, eligible lands were identified, field reconnaissance was conducted across 143 test sites, and the 3-PG model of Headlee et al. [45] was refined to estimate poplar productivity within the suitable areas. Two changes were made to the original model. First, SSURGO soil data replaced STATSGO soil data, resulting in increased mapping resolutions. Second, to capture the potential implications of genotypic selection, two clonal groups were tested. Estimates for *generalist clones*, defined as those performing well across the region, were developed using the default settings from Headlee et al. [45] and SSURGO soil data. In contrast, productivity for *specialist clones*, defined as

those adapted to specific locations, was modeled as with generalist clones plus the adjustment of setting the optimum temperature for growth equal to each site's mean maximum growing season temperature (June to August) [9]. Overall, hybrid poplar productivity ranged from 9.5 to 11.9 dry Mg ha<sup>-1</sup> year<sup>-1</sup>, with a mean of 10.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup>. Specialist clones exhibited an 18 % increase in productivity potential compared with their generalist counterparts, thereby expressing the importance of considering genotype × environment interactions when deploying hybrid poplars in the region, regardless of end use.

### Cottonwood

Eastern cottonwood (*P. deltoides*) is a prime candidate for SRWC because it is the fastest growing tree in North America and is easy to propagate vegetatively [69, 103]. Eastern cottonwood is one of the tallest hardwood species, achieving heights of 53–59 m in natural stands with diameters of 120–180 cm [104, 105]. Cottonwood is intolerant of shading, with much variability among clones. Generally, crowns of cottonwood do not touch even in closely spaced plantings and belowground competition may commence before crown closure [106]. Individual tree volume equations were developed by Krinard [107] and form the basis for the compatible growth and yield model developed by Cao and Durand [108]. Site index, developed from stand data, is used in the model; polymorphic site index curves for cottonwood plantations in the Lower Mississippi Alluvial Valley for base age 10 years were developed by Cao and Durand [109]. In plantations, the mean annual height growth at age 10 was reported as 1.9–2.4 m year<sup>-1</sup> [108].

Cottonwood grows best on well- and moderately well-drained soils and most clones do not tolerate saturation and anaerobic soil conditions during the growing season [69]. Expanding cottonwood to less favorable sites will require identification of adapted clones. The need to control competing vegetation early in the rotation presents a limitation on some heavy-textured soils due to equipment limitations that make weed control difficult as well as increased costs. Improved genetic material and other advances in SRWC culture could produce higher productivity than has been achieved in industrial pulpwood plantations, which have sustained yields of more than 10.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup> [69]. Proven clones on good sites, tended with appropriate and timely cultural treatments, in 5 years can produce more than 13.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup> [110]. Potential SRWC yields, with higher initial density and shorter rotations, have been estimated as 27.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup> [111, 112]. Advanced breeding to match clones to site, and for disease resistance and appropriate silvicultural practices, will be needed to achieve a doubling of productivity.

### Loblolly Pine

The establishment of the Southern Forest Experiment Station in New Orleans, LA, and the Appalachian Forest Experiment Station in Asheville, NC, by the USDA FS was a milestone in the development of forestry and forest research in the South [113]. The actual and potential productivity of southern pine species became apparent with the publication of Miscellaneous Publication 50 [114], and the technology for establishing pine plantations on cutover land was advanced by the work of USDA FS scientist Dr. Philip Wakeley [115]. Half a century of research and breeding by USDA FS, forest industry, and university scientists and implementation by forest industry and other large private landowners have produced plantations of loblolly pines that grow ten times faster than naturally regenerated stands [116–118]. Of the southern pines, loblolly pine exhibits the fastest early growth and is the most responsive to amendments [21]. Genetic improvement of planting stock, along with advances in silvicultural techniques and a well-developed value chain, provides a broad foundation for SRWC pine. Over the years, USDA FS scientists have contributed directly and through cooperative research programs to the development of plantation pine culture, including growth and yield [119–124].

There is relatively little published information on the use of loblolly pine for SRWC, but before forest industry divested much of their land in the 1990s, they experimented with SRIC for pulpwood. By controlling height growth losses to Nantucket pine tip moth (*Rhyacionia frustrana* Scudder in Comstock), they obtained annual growth increments of 3.1–3.6 dry Mg ha<sup>-1</sup> at ages 10–12 years on some sites [117, 125] and on most sites routinely obtained annual increments averaging 2.1–2.7 dry Mg ha<sup>-1</sup> [126, 127]. Studies comparing planting density and genotypes provide insight into potential growth under SRWC. For example, there was no difference in growth under two dense plantings (3700 and 4400 trees ha<sup>-1</sup>) after 4 years and stem biomass growth in the fourth year was 17.4 dry Mg ha<sup>-1</sup> [128]. Using the same improved family, Adegbi et al. [129] reported biomass accumulation from four intensively managed stands planted at the same density, 1495 trees ha<sup>-1</sup>. After 4 years, stemwood growth was 10.1 dry Mg ha<sup>-1</sup> year<sup>-1</sup> and accounted for 34 % of the net primary production.

### Eucalypts

Short-rotation *Eucalyptus* potentially could produce more biomass than loblolly pine if frost-tolerant site-adapted genotypes can be identified. Short rotation systems in Peninsular Florida using *E. grandis* and cabbage gum (*Eucalyptus amplifolia* Naudin) can produce up to 67.0 green Mg ha<sup>-1</sup> year<sup>-1</sup> in multiple 3-year rotations [83]. Appropriate sites are likely on soils of sandy clay

loam and clay loam textures and moderately well- to well-drained soils, avoiding sites with imperfect or excessive drainage [70]. Managing competing vegetation and developing appropriate fertilization regimes are needed to achieve high levels of productivity [70]. Weed control treatments are not well developed for eucalypts in the South; herbicides used for pine culture are not appropriate for eucalypt plantations. Because *Eucalyptus* spp. are not native to North America, there is concern for their potential invasiveness and effects on natural ecosystems [130]. Potential invasiveness was investigated based on field assessment of actual escapes from *Eucalyptus* plantings on three sites in South Carolina and 16 sites in Florida [131]. They found a small number of *E. amplifolia*, *E. robusta*, and *E. grandis* seedlings growing within and nearby to *Eucalyptus* plantations at four sites in Florida, but only two individuals were detected more than 45 m from plantation boundaries.

Callaham et al. [131] concluded that the invasiveness potential for *Eucalyptus* species considered for the Southern USA is generally low. The species with the greatest potential for the Southern USA have limited ability to disperse and produce small seeds with low viability. Seedlings are light-demanding and grow poorly under closed forest or understory canopies. Some eucalypt species may naturalize (spontaneously reproduce in their introduced range) in the South, but there was no evidence for invasion (reproducing and spreading long distances, i.e., hundreds of meters in large numbers). Nevertheless, Callaham et al. [131] cautioned that the potential for spread into unmanaged areas should not be dismissed.

Another potential concern for expanding eucalypt plantations in the South is increased fire risk. Goodrick and Stanturf [132] examined the effect of widespread plantings of eucalypts on the risk of wildfires and whether fire behavior in eucalypt stands would differ from fires in commonly occurring vegetation types such as pine plantations. They used the Fuel Characteristic Classification System and literature values for fuel characteristics and loads to model surface fire behavior in young *Eucalyptus* plantations and found little difference as compared to surface fires in fuels common to pine forests characteristic of the Lower Coastal Plain. Spotting behavior (i.e., when a fire produces sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire) is a characteristic of eucalypts that existing models do not adequately account for, but stands managed on short rotation (less than 10 years) will likely be harvested before bark shedding presents a significant spotting problem. Fires are more likely to start outside *Eucalyptus* plantations than inside, but once a crown fire is initiated, it will spread rapidly and the potential is for more severe crown fire behavior than in pine stands.

### Cottonwood, Loblolly Pine, and Eucalypts

The genus-specific research described above is very important for the advancement of SRWC production systems. However, there is a need for additional studies comparing these genera (and their species) side-by-side across multiple temporal and spatial scales. Currently, 3-PG is being used to account for environmental influences on tree growth while comparing the productivity potential of cottonwood, loblolly pine, and eucalypts across a range of environmental conditions in a quantitative, spatially explicit manner [133]. The specific objectives of this research include: (1) adapting the 3-PG model for cottonwood, loblolly pine, and eucalypts within the southeastern USA; (2) using existing geographic information system (GIS) layers for soils and climate to generate productivity estimates within the region by climate zone and soil type; and (3) determining the optimum (i.e., highest economic value) species and rotation age by climate zone and soil type. Preliminary outcomes of model fitting and mapping efforts, assuming low-intensity management and planting densities typical of each species, indicate that peak productivity of 9.5–15.7 dry Mg ha<sup>-1</sup> year<sup>-1</sup> can be expected for eucalypts on 3- to 4-year rotations, 12.2–17.2 dry Mg ha<sup>-1</sup> year<sup>-1</sup> for loblolly pine on 13- to 15-year rotations, and 9.6–18.6 dry Mg ha<sup>-1</sup> year<sup>-1</sup> for poplars on 12- to 13-year rotations [134]. In the northern part of the region, productivity estimates for loamy and clay soils were highest under poplar production, whereas they were highest on sandy soils with loblolly pine; in the southern part of the region, productivity estimates were generally highest for eucalypts across soil types.

### Yield

#### Hybrid Poplar

In the southeastern USA, the survival and growth of 31 pure species and hybrid *Populus* selections were evaluated on an upland sandy and bottomland sandy loam site [25]. All trees received irrigation at the upland site, while trees received irrigation or no irrigation (control) at the bottomland site. One pure *P. deltoides* selection and two *P. trichocarpa* × *P. deltoides* hybrids accumulated the most stem volume (ranging from 25.6 to 31.6 dm<sup>3</sup>) after 3 years at the upland site. The hybrid clones originated in the Pacific Northwest, while the pure *P. deltoides* was from Mississippi. At the bottomland site, pure *P. deltoides* selections (one from Arkansas and one from Mississippi) accumulated the most stem volume (ranging from 17.5 to 20.8 dm<sup>3</sup>) after three growing seasons, and irrigation resulted in substantial growth increases. These studies highlight the importance of irrigation in the absence of a natural water source for *Populus* growth in the southeastern USA. These trees were also evaluated after ten growing seasons [26]. Early survival (i.e., up to 3 years old) correlated

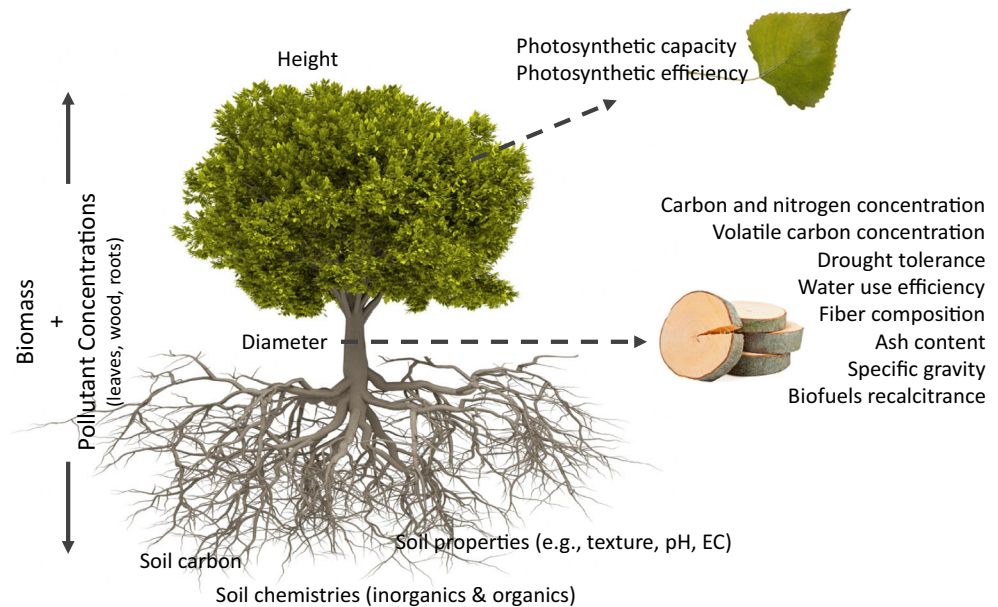
well with survival after 10 years, and stem volume of 3-year-old trees correlated well with stem volume after 10 years on an upland site. This work supports the screening of multiple *Populus* selections if they are to be a viable biomass alternative in the southeastern USA. These data are needed to find selections that will both survive and produce in the warm climate and on (often) sandy, non-alluvial soils.

In the North Central USA, the gap between hybrid poplar yields in small-plot versus field-scale trials has decreased in the past decades, making hybrid poplars more economically feasible in some areas [102]. However, despite promising gains from selection coupled with increased silvicultural knowledge, genotype × environment interactions continue to dominate yields [22]. Hansen [135] published one of the first papers on hybrid poplar yield potential, where estimates ranged from 7.6 to 15.7 dry Mg ha<sup>-1</sup> year<sup>-1</sup> in Wisconsin. Along with others, he later reported that superior clones in small-plot trials exhibited 300 %, and those in field trials 200 %, greater yield than commercial clones at mid-rotation [79]. At rotation age (i.e., 10–12 years), Netzer et al. [46] reported similar results from many of these same sites.

There are two notable examples of recent USDA FS hybrid poplar yield research in the North Central USA. First, the US Department of Energy at the Oak Ridge National Laboratory funded a regional field testing network that spanned four states (Iowa, Michigan, Minnesota, Wisconsin), three planting years (1995, 1997, 2000), and roughly 200 genotypes belonging to 10 genomic groups [23]. Zalesny et al. [22] conducted a remeasurement campaign and reported that new, superior clonal selections exhibited 1.4–2.7 times as much biomass as commercial clones and that some of these selections had mean annual increments greater than 20.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup> (i.e., 50 % greater biomass than estimates for previous superior selections). Second, with funding from the USDA FS R&D Washington Office Woody Biomass, Bioenergy, and Bioproducts Program, Northern Research Station scientists have partnered with university collaborators to develop an integrated network from the original Hansen et al. [79] and Riemenschneider et al. [23] trials to test long-term ecosystem services of hybrid poplars, with biomass yield being one of these services. The resultant ecosystem services network that is also currently being used for carbon (see below), water use (see below), and conversion [47, 48, 136] studies (Fig. 2) is comprised of 11 of the original Hansen et al. [79] sites (i.e., 20-year-olds) and four of the original Riemenschneider et al. [23] plantings (i.e., 10-year-olds) located in Iowa, Michigan, Minnesota, and Wisconsin (Fig. 1). In total, 12 clones belonging to five genomic groups are being tested, with 10 clones from the 10-year-old network and two clones from the 20-year-old plantations (Table 2). Site × clone interactions governed yield for both age groups (10 years,  $P=0.0421$ ; 20 years,  $P<0.0001$ ). For the 10-year-old trees, the interaction means of biomass ranged from 3.3 to 16.9 dry Mg ha<sup>-1</sup> year<sup>-1</sup>,



**Fig. 2** Ecosystem services (biomass, carbon, water, soils) and associated allometric and physiological traits of *Populus* tested in multiple woody crop production system networks in the USA (see Fig 1)



with an overall mean of 8.7 dry Mg ha<sup>-1</sup> year<sup>-1</sup>. The least biomass was from a *P. deltoides* × *P. deltoides* F<sub>1</sub> hybrid ('C918001') growing in Escanaba, MI (45.77°N, 87.20°W), while the most biomass was from another hybrid from that genomic group ('C916400') growing at Arlington, WI (43.29°N, 89.37°W). For the 20-year-old trees, the interaction means of biomass ranged from 5.8 to 21.7 dry Mg ha<sup>-1</sup> year<sup>-1</sup>, with an overall mean of 11.9 dry Mg ha<sup>-1</sup> year<sup>-1</sup>. Of particular note is the biomass yield of clone 'DN182', a *P. deltoides* × *P. nigra* F<sub>1</sub> hybrid, that exhibited greater than 18.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup> at three sites [Rhineland, WI (45.63°N, 89.46°W); Granite Falls, MN (44.80°N, 95.52°W); and Fairmont, MN (43.69°N, 94.35°W)]. This yield is more than three times higher than those reported in Hansen et al. [79], indicating that silvicultural research was successful at increasing yields in the region.

### Cottonwood

A long-term replicated experiment was established in 2000 at the USDA FS Southern Research Station Savannah River Site in New Ellenton, SC (33.38°N, 81.67°W) [27] (Fig. 1). Two pure *P. deltoides* clones ('ST66' of Mississippi origin and 'S7C15' of East Texas origin) were included in this study that measured growth and productivity responses to varying levels of irrigation and fertilization. In a non-replicated experiment designed to find optimal nitrogen fertilization rates [28], the optimal nitrogen fertilization rates were 131 and 71 kg N ha<sup>-1</sup> year<sup>-1</sup> for irrigated and non-irrigated 'ST66', respectively. Maximum aboveground biomass differed little, however, between irrigated and non-irrigated trees (i.e., range from 3.6 to 4.3 dry Mg ha<sup>-1</sup> year<sup>-1</sup>). Clone 'S7C15' was more N-demanding, as the optimal rate for irrigated trees was

232 kg N ha<sup>-1</sup> year<sup>-1</sup> and for non-irrigated trees was 94 kg N ha<sup>-1</sup> year<sup>-1</sup>. Furthermore, growth responses for 'S7C15' differed greatly between irrigated (6.3 dry Mg ha<sup>-1</sup> year<sup>-1</sup>) and non-irrigated (2.9 dry Mg ha<sup>-1</sup> year<sup>-1</sup>) trees. Overall, the use of irrigation would not be economically feasible for these two *P. deltoides* clones in this area, or likely on this type of soil throughout the southeastern USA.

Furthermore, the growth of both clones was significantly improved by increasing resource availability throughout the harvest rotation [29, 30]. After nine growing seasons, aboveground woody production was 7.2 and 6.4 dry Mg ha<sup>-1</sup> year<sup>-1</sup> in 'ST66' and 'S7C15', respectively [30]. Irrigation and fertilization resulted in aboveground productivity increases of >177 %. The relative proportion of above- and belowground tissue allocation was affected by both tree size and resource availability [30].

Research directed at eastern cottonwood yields in the Mississippi Alluvial Valley (MAV) has not kept pace with SRWC in other regions primarily due to a lack of industrial plantation management in the region. Two companies that most recently managed industrial plantations in the region, Tembec (formerly Crown Vantage) in Fidler, MS, and Westvaco in Wickliffe, KY, terminated cottonwood management and sold their holdings in 1998 and 2007, respectively. The vast majority of eastern cottonwood plantations established in the region today are intended for forest restoration, carbon sequestration, wildlife habitat, and recreational purposes [137]. In the late 1980s, Krinard [107] released volume equations for plantation-grown eastern cottonwood, and these equations are still used today for predicting cubic volume of individual trees. In 1991, Cao and Durand [108] published the first growth and yield model to predict whole-stand volume for eastern cottonwood plantations in the MAV. This

model was developed from cottonwood plantations throughout the southern half of the MAV [108], and it appears to conform well to operational yields produced locally [138].

The Cao and Durand [108] model is a compatible growth and yield model that predicts cubic-foot volume yield and projects volume from site index, initial age, and basal area. The model was the basis for an Excel spreadsheet called Cotton, prepared by Cao for Crown Vantage (later Tembec) in 1994. Stanturf and Portwood [138] used this software to estimate volume to a 7.5-cm top and yield of green megagrams per hectare for stands on three representative soil/site productivity classes to evaluate the economic potential of pulpwood rotations of 10 and 11 years. These soils are suitable for growing cottonwood, but vary in productivity. Stocking and height measurements at age 3 were taken from stands on the Fitler Plantation, on old-field sites, protected by the river levee, with good survival. Stands were planted with improved stock, fertilized at site preparation, and competing vegetation was controlled with herbicides [138].

The modeled yields are shown in Table 3. The stand on the Commerce soil (Aeric Fluvaquents) represented the highest productivity sites and yielded 76.7 dry Mg ha<sup>-1</sup> at age 10. The medium productivity sites on Tunica-Bowdre soils (Vertic Haplaquents-Fluvaquentic Hapludolls) and the lowest productivity sites on the Sharkey soil (Vertic Haplaquents) yielded considerably less, 56.0 and 47.0 dry Mg ha<sup>-1</sup>, respectively. One deficiency of the model is that it is not valid for coppice rotations, and operational experience from the Fitler plantation indicates that merchantable yields from stands of coppice origin are typically reduced by half because most trees develop with multiple stems [138]. Byrd et al. [139] recently attempted to develop a simple model for predicting aboveground biomass of multi-stemmed eastern cottonwood, but the authors were not satisfied that their model was useful across a range of soil types and regeneration methods. While coppicing results in a loss of merchantability for pulp markets, this may or may not be an issue for biomass markets, but a robust growth and yield model for stands of coppice-origin eastern cottonwood remains unavailable for the MAV.

### Loblolly Pine

The growth and productivity of loblolly pine selection ‘7–56’ was evaluated over an 11-year harvest rotation (i.e., from 2000 to 2010) on a sandy upland site in South Carolina (33.38°N, 81.67°W). Trees received irrigation (0.5 cm day<sup>-1</sup>, for a total of 3.0 cm week<sup>-1</sup>), fertilization (120 kg N ha<sup>-1</sup> year<sup>-1</sup>), and irrigation + fertilization or were untreated (control). Loblolly pine did not respond to irrigation during early [31] or late [30] development, indicating that fertilization was the primary limiting factor of tree productivity. Maximum aboveground woody production of loblolly pine exceeded 19.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup>, and annual stem productivity was nearly 10.0 dry Mg ha<sup>-1</sup> year<sup>-1</sup>. With fertilization, trees reached a basal area at which thinning is required at 8 years of age—3 years sooner than without fertilization (control). Trees allocated more biomass to belowground tissues as resource availability increased, even as trees increased in size [30].

### Pest Susceptibility: Resistance Screening and Impacts on Growth

Short-rotation woody crop systems are known to be susceptible to a number of insect pests [32], and work at the Savannah River Site (Fig. 1) supported examining of the influence of resource availability on tree susceptibility to pests. Pest infestations occurred on several tree genera over the course of the growing rotation. The cottonwood leafcurl mite, *Aculops lobuliferus* Keifer, causes premature leaf curling and abscission, and terminal mortality, early in the rotation [33]. The mite showed preference for ‘S7C15’ during spring and ‘ST66’ during summer and fall. Miticide applications successfully controlled the pest infestation, but not before several instances of high defoliation. In general, mite damage was greatest on fertilized trees. Shortly after the mite infestation, several species of ambrosia beetles attacked live *P. deltoides* trees—a relatively rare occurrence for this insect group [32]. Clone ‘ST66’ was more susceptible than ‘S7C15’, and the highest attack rates were found on fertilized trees. A leafhopper, *Erythroneura lawsoni* Robinson, had very high

**Table 3** Estimated cottonwood plantation yields in the Lower Mississippi Alluvial Valley at rotation age 10 years on three representative soil/site productivity classes (stands were age 3 years when measured) (adapted from [138])

	Site		
	Commerce	Tunica-Bowdre	Sharkey
Site index (m; base age 10)	24.1	22.3	20.1
Basal area (m <sup>2</sup> ha <sup>-1</sup> )	6.7	3.9	3.4
Stems (ha <sup>-1</sup> )	682	622	642
Survival percent	91	83	86
Yield at age 10 years (dry Mg ha <sup>-1</sup> )	76.7	56.3	47.1
Cumulative annual increment (dry Mg ha <sup>-1</sup> , age 10)	8.4	7.0	6.0
Mean annual increment (dry Mg ha <sup>-1</sup> , age 10)	7.7	5.6	4.7



populations in sycamore, and while little foliar feeding injury occurred, higher numbers of leafhoppers were generally captured in non-fertilized plots [66]. In loblolly pine, irrigation and fertilization did not consistently impact Nantucket pine tip moth damage levels or pupal weight [64].

Cottonwood leaf beetle (*Chrysomela scripta* F.), cottonwood leafcurl mite, and poplar leaf rust (*Melampsora medusa* Thüm) incidence and damage were monitored on 31 *Populus* clones over 3 years in South Carolina [34]. Irrigated trees had significantly greater cottonwood leaf beetle and poplar leaf rust damage levels in each year, and damage tended to increase throughout the growing season. Clone rankings varied widely among clones and years, depending on the specific pest and environment. For instance, *P. deltoides* × *P. nigra* clones ‘OP367’ and ‘I45-51’ and the *P. trichocarpa* × *P. nigra* clone ‘311-93’ were most resistant to the cottonwood leaf beetle on the upland site, but pure *P. deltoides* clones ‘S7C1’ and ‘7302801’ and the *P. nigra* × Japanese poplar (*Populus suaveolens* Fischer subsp. *maximowiczii* A. Henry) clone ‘NM6’ were most resistant on a bottomland site. Furthermore, clones ‘OP367’, ‘7302810’, and the *P. deltoides* clone ‘ST109’ were most resistant to the cottonwood leafcurl mite on an upland site, while ‘NM6’, ‘I45-51’, and the *P. deltoides* × *P. suaveolens* subsp. *maximowiczii* clone ‘Eridano’ were most resistant on a bottomland site. Clones ‘NM6’, ‘I45-51’, and the *P. trichocarpa* × *P. deltoides* clone ‘15-29’ were highly resistant to leaf rust on both sites.

## Bioenergy Siting Applications

In addition to the biological productivity of these SRWC, USDA FS researchers and their collaborators have made substantial progress on understanding the economic drivers of woody biomass. In particular, since 2007, the Southern Research Station and the University of Tennessee have partnered to develop a biomass and bioenergy assessment collaborative. Since that time, the collaborative has added other universities and federal agency partners to conduct research for the development, enhancement, and deployment of innovative decision support tools.

The Biomass Site Assessment Tools (BioSAT) partnership delivers landscape-scale decision support and web-based assessments for agricultural, grassland, and forest ecosystems (Fig. 3). The “genesis” of BioSAT grew from the knowledge that stability of the biomass markets depends on improved methods to display the risk and cost of supply and logistics from farms and forests to collection or conversion facilities. The context was to develop an integrated resource assessment model to spatially define and compare socioeconomic and biophysical drivers paired with community-based human–environmental conditions impacting the bio-economy.

## Conceptual Framework

The collaborative is responsive to research needs expressed in the literature and reports on the economic availability of biomass including: (1) US Department of Energy US Billion-Ton Study [140], (2) US Billion-Ton Update [6], (3) USDA FS Woody Biomass Utilization Strategy [141], and (4) USDA FS Strategic Energy Framework [142].

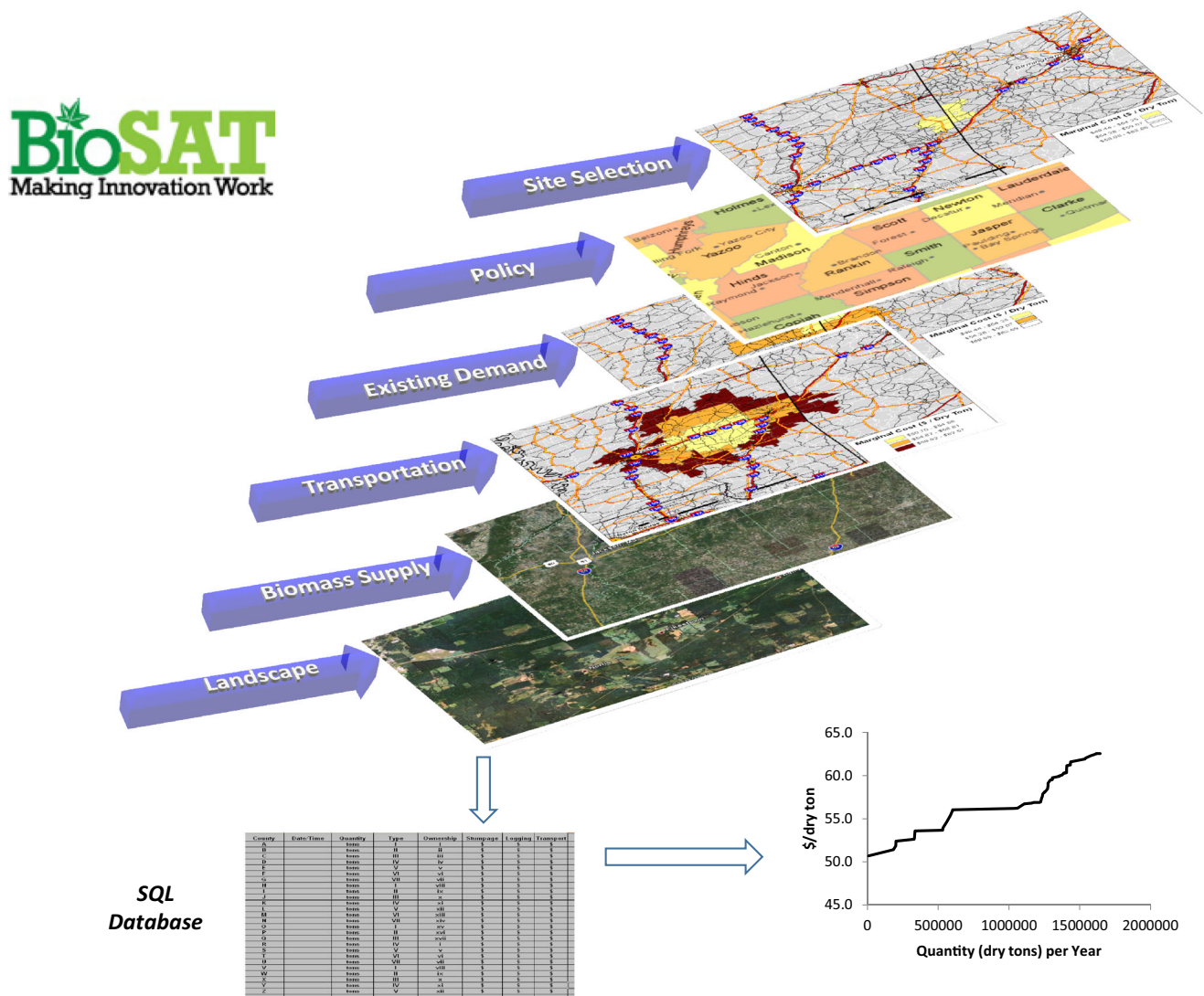
As noted, one of the first challenges for any commercial activity is to determine where suitable and available lands are located [143]. Site selection must consider biological, economic, and societal factors with information on soils, geology, vegetation, current land uses, topography, etc., compared and spatially defined using GIS. Potential constraints on the availability of biomass feedstock also need to be better understood [144]. Primary constraints include a lack of production capacity along with the high relative costs of production, logistics, and transportation.

Constraints within the natural, built, and social environments limit available biomass supplies. These constraints affect the amount and type of biomass potentially available locally, as well as at broader landscape scales. To address these constraints, USDA FS researchers are working with partners to develop decision-making tools that support intelligent alignment of the production and use of biomass with other existing ecological, social, and economic objectives [145]. Developing the new bio-economy involves understanding and establishing many complex relationships [146–148].

## Methods

Assessing the bio-economy is not straightforward. The bio-based sector of the US economy is multidimensional. There is the lack of clear definition of what attributes, indices, or combinations best measure the bio-economy. Multiple-attribute landscape characterization helps decision-makers discover potential risks and opportunities for local lands. Composite indices visually summarizing information from an array of individual attributes provide a clear picture for the public, industry, media, and policy makers. The data and analyses are not meant to represent the total state of a geographic region, but rather to demonstrate what types of information give reasonable measures of the landscape conditions and opportunities for developing a bio-based economy. Researchers use the results of ongoing studies to explore additional attributes with the intent of adding value and improving the reliability of the spatially defined framework.

More than 125 attributes have or are being explored for use as indices within BioSAT (Table 4). These attributes belong to seven categories: (1) initial siting and economic indices and models (26 attributes); (2) opportunity zone indices and model (×12); (3) SRWC production indices and model (×51); (4) race and origin of population in the USA (×13); (5) natural



**Fig. 3** Conceptual diagram of BioSAT, a model that fuses layers of spatial and economic data together to create a relational database for geographic-based economic cost assessment for woody and agricultural residue biomass collection or processing demand centers

disaster vulnerability indices ( $\times 16$ ); (6) carbon ( $\times 8$ ); and (7) plant-available soil water holding capacities to 1.5-m depth ( $\times 1$ ).

### Approaches and Results

**Phases I and II** BioSAT integrates contemporary web-based information technology (e.g., Virtual Earth and Microsoft SQL) with existing data: *forestry* [USDA FS Forest Inventory and Analysis (FIA)]; *agriculture* [USDA National Agriculture Statistics Service (USDA NASS)]; *harvesting* [USDA FS Fuel Reduction Simulator (FRCS), Auburn Harvest Analyzer (AHA)]; and *transportation* (enhanced model by [149]).

The BioSAT applications data, models, and results provide spatially explicit indices for bio-basins. The sub-county multidimensional framework is used to conduct analyses to

evaluate various aspects of growth, profitability, and uncertainty. All records are organized at a five-digit ZIP Code Tabulation Area (ZCTA) resolution and matched with zip codes. The average area for the five-digit ZCTAs in the 33-state study region is about 169 km<sup>2</sup>. The five-digit ZCTAs result in more than 25,000 potential analytical polygons or site locations. The model uses relatively simple and readily available GIS-based landscape characterization and socioeconomic inputs to derive and generate visual evidence of biomass supply/demand, risk potential, biomass accessibility and landscape suitability, opportunity zones, energy crop production potential, and ecological vulnerability. The BioSAT decision support tools are available at <http://www.biosat.net/>.

Research reports and journal publications outline the process, results of analysis, and the relevance of selected indices to measure the potential of the bio-economy. With a focus on supply chain components, the system maps and

**Table 4** BioSAT model inputs and outputs (adapted from the BioSAT public domain website, [www.BioSAT.net](http://www.BioSAT.net))

Input variable	Collection level	Unit	Data source (current date)	Output
Forest pulpwood	County	Dry tons	USDA FS FIA (2005–2010)	BioSAT model estimates for biomass quantities (dry tons)
Forest sawtimber	County	Dry tons	USDA FS FIA (2005–2010)	BioSAT model estimates for biomass quantities (dry tons)
Logging residues	County	Dry tons	USDA FS FIA/SRTS model (2006–2010)	BioSAT model estimates for biomass quantities (dry tons)
Mill residues	County	Dry tons	USDA FS TPO (2009)	BioSAT model estimates for biomass quantities (dry tons)
Ag residues	County	Dry tons	USDA NASS (2009)	BioSAT model estimates for biomass quantities (dry tons)
Crop-cultivated land area ratio	5-digit ZCTA <sup>a</sup>	Percent	U.S. National Land Cover Database (2006)	Allocation of inventory at 30 × 30-m resolution (spatial)
Forest land area ratio	5-digit ZCTA	Percent	U.S. National Land Cover Database (2006)	Allocation of inventory at 30 × 30-m resolution (spatial)
Pulpwood stumpage	Intrastate and state	US\$ dry ton <sup>-1</sup>	Timber Mart South (2012) Timber Mart North (2012) Reporting by state agencies (2009–2012)	BioSAT model resource costs for biomass (US\$ dry ton <sup>-1</sup> )
Sawtimber stumpage	Intrastate and state	US\$ dry ton <sup>-1</sup>	Timber Mart South (2012) Timber Mart North (2012) Reporting by state agencies (2009–2012)	BioSAT model resource costs for biomass (US\$ dry ton <sup>-1</sup> )
Mill residue prices	Intrastate and state	US\$ dry ton <sup>-1</sup>	Timber Mart South (2012) Timber Mart North (2012) Reporting by state agencies (2009–2012)	BioSAT model resource costs for biomass (US\$ dry ton <sup>-1</sup> )
Harvesting costs for roundwood (5 options)	EcoRegion	US\$ dry ton <sup>-1</sup>	Auburn Harvesting Analyzer enhanced for BioSAT	BioSAT model harvesting costs for biomass (US\$ dry ton <sup>-1</sup> )
Harvesting costs for logging residues (2 options)	EcoRegion	US\$ dry ton <sup>-1</sup>	USDA FS FRCS Model	BioSAT model harvesting costs for biomass (US\$ dry ton <sup>-1</sup> )
Harvesting costs for ag residues (2 options)	County	US\$ dry ton <sup>-1</sup>	Literature	BioSAT model harvesting costs for biomass (US\$ dry ton <sup>-1</sup> )
Travel distance	5-digit ZCTA	Miles	Microsoft MapPoint (2009)	BioSAT model trucking model (US\$ dry ton-mile <sup>-1</sup> )
Travel time	5-digit ZCTA	Minutes	Microsoft MapPoint (2009)	BioSAT model trucking model (US\$ dry ton-mile <sup>-1</sup> )
Diesel prices	State	US\$ gallon <sup>-1</sup>	U.S. Energy Information Agency (2012)	BioSAT model trucking model (US\$ dry ton-mile <sup>-1</sup> )
Labor rates	State	US\$ hour <sup>-1</sup>	Reporting by state agencies (2010)	BioSAT model trucking model (US\$ dry ton-mile <sup>-1</sup> )
License and tax rates	State	US\$ year <sup>-1</sup>	Reporting by state agencies (2010)	BioSAT model trucking model (US\$ dry ton-mile <sup>-1</sup> )
Truck weight limits	State	Dry tons	Reporting by state agencies (2010)	BioSAT model trucking model (US\$ dry ton-mile <sup>-1</sup> )
Intra truck-rail locations	5-digit ZCTA	Latitude longitude	Reporting by rail companies (2010)	BioSAT model rail-truck locations (spatial)

Overall outputs include total, average, and marginal costs for biomass in a spatial context for opportunity zones and bio-basins, as well as marginal cost curves or producer supply curves in a spatial context for opportunity zones and bio-basins

<sup>a</sup> 5-digit ZCTA five-digit zip code tabulation area. All GIS analysis levels were at the five-digit ZCTA

displays baseline data for public and business leaders, assesses the economic availability of woody and agricultural-derived biomass, identifies local market

conditions, and thereby reduces screening time to locate sites favorable for full economic or business case due diligence [150–153].

The following phases built upon the initial research to improve and extend the utility of the web-based system.

**Phase III: The Wood to Energy Project** The objectives included providing a complete literature review on the state of the science and developing a database of wood-to-energy-related industries in the USA and Canada. The database includes major forest product industries that produce residues, users of residues for energy (e.g., boilers, ethanol producers, etc.), and related industries. Such information is vital to making sound planning and business decisions to expand uses of wood for energy. The system is being continuously updated to ensure that it is comprehensive as it is practical [154].

#### **Phase IV: Logistic Regression Models of Factors Influencing the Location of Bioenergy and Biofuel Plants**

In addition to the broad range of forest types across the country, there are regional and local differences in silvicultural systems, demand for traditional wood products, land use, landowner attitudes, energy opportunities, and local and state policies [155]. Phase IV builds upon previous research and is the first study to use logistic regression models to quantify significant factors influencing site location of woody biomass-using bioenergy and biofuel plants and predict potential locations based on probability. The logistic regression model is the most widely used method to relate a binary outcome (i.e., success/failure) to a set of explanatory variables in a regression setting. Logistic regression models were developed to identify significant factors that influence the location of existing wood-using bioenergy/biofuel plants and traditional wood-using facilities. Existing data on favorable and unfavorable locations for woody biomass-using facilities were used to train logistic regression models. These models were then used to evaluate the suitability of new locations. Economic factors, transportation-related factors, and the availability of biomass feedstocks were included as predictor variables in the logistic regression models. A de-clustering algorithm was developed to move sites identified by the logistic models away from sources of competition. Based on the logistic models, 25 locations were predicted for bioenergy or biofuel plants for a 13-state study region in the Southern USA [153].

#### **Phase V: A Spatial Index for Identifying Opportunity Zones for Woody Cellulosic Conversion Facilities**

The use of renewable biomass can help diversify markets for agriculture and forestry, create jobs, and promote rural development [156, 157]. There are many factors that influence the amount of biomass that is actually available. Phase V integrates geographical landscape characterization and socioeconomic GIS data with BioSAT to display and visualize the risk while identifying opportunity zones for potential biomass-using facilities (e.g., biorefineries, wood pellet mills, biopower) [152, 153,

158]. Emerging opportunities that compete against existing uses of property or raw resources are often socially constrained or permanently denied regardless of economic viability. The opportunity zones are derived from the use of landscape suitability and competition indices. Landscape features (measure to which a competing land use is physically restricted by current land use) may adversely impact economically viable competing uses of property and thereby restrict biomass access and positive location decisions. Spatial competition is particularly important for access to biomass resources. Existence of competing biomass-using facilities reduces the probability of making a positive location decision, and this impact decreases with distance from competition. Landscape and competition indices were developed in the study, and combining these indices in a spatial-geographic context derives a classification of “opportunity zones” for potential users of woody cellulosic feedstocks [159].

#### **Phase VI: An Economic Geospatial Analysis of SRWC**

Short-rotation woody crops are part of the bioenergy solution in the USA [160], especially in the Southeast where plantation forestry is economical [116]. Currently, SRWC productivity is not cost-effective; assessing optimal site locations for large geographic regions is essential for lowering costs [9, 102, 111]. Short-rotation woody crops are ideal renewable feedstocks because they can be strategically located near conversion facilities and provide ecological services, conserve soil and water, recycle nutrients, and sequester carbon [65]. To that end, the objective of phase VI was to improve the economic assessments of SRWC based on the suitability of lands and enhance the economic assessments in a geospatial context. With BioSAT, the when and where of production and logistics of SRWCs were identified to build efficiencies for profitability and sustainability of biomass supply chains, assuming deployment in conjunction with potential facility locations. Risk probabilities for SRWC production and processing locations using Bayesian inference are unique to SRWC research. Site requirements for four genera (*Populus*, *Salix*, *Pinus*, and *Eucalyptus*) are defined that have the potential for large-scale production. Soils, climatology, 3-PG modeling, and land cover data are developed and will be fused with existing BioSAT model physiognomic, economic, and societal data for 33 Eastern US states [161].

#### **Phase VII: Modeling the Impact of the Emerging Bio-economy on Transportation Network Flows with Simulation and Bayesian Inference**

The impact of the emerging bio-economy on transportation infrastructure and related concerns is a top priority for the US Department of Transportation and Southeastern Sun Grant Program. Phase VII addressed this priority through modeling of specific impacts of the emerging bio-economy on truck transportation network flow for the Southern US. In phase VII, Bayesian



logistic regression and GIS spatial analysis were applied to estimate site locations for biorefineries in the presence of uncertainty as related to resource competition, delivered costs at the plant gate, and trucking transportation flow. Procurement zones assumed a one-way haul distance of 129 km as a function of the available road network and interrelated resource as estimated from the BioSAT model. Attributes such as *median family income*, *timberland annual growth-to-removal ratio*, and *transportation delays* were highly significant in influencing mill location. Transportation delays for trucks greatly impacted the cost of trucking biomass resources. For example, trucking costs increased 60 % in some areas of the Southern USA. The logistic model using Bayesian inference was a good model for predicting preferred site locations and identifying non-preferred locations [162].

## Carbon

### Southeast Region

In the MAV, a region in which agricultural land use predominates, interests in carbon (C) sequestration have played a prominent role in the restoration of farmland to forests [163]. In 1994, scientists and collaborators at the Center for Bottomland Hardwoods Research in Stoneville, MS, initiated work on the Sharkey Restoration Research and Demonstration Site (32.96°N, 90.74°W), an area devoted to the study of forest restoration on farmed bottomlands in the MAV (Fig. 1) [164]. A primary focus of the research has been an afforestation system inspired from knowledge of developmental patterns of natural eastern cottonwood stands [164]. The eastern cottonwood–hardwood interplanting system provides a novel approach for C sequestration on former agricultural lands. Accumulation of above- and belowground biomass is maximized by the eastern cottonwood nurse crop during the initial stages of stand establishment and maintained through the life of the stand by development of the slower-growing, later-successional interplanted hardwoods. Modeling the C balance of these plantations projects an annual C gain greater than 9.0 Mg C ha<sup>-1</sup> over a 100-year rotation. Ongoing long-term research will enable further calibration of C storage models for variation resulting from stand dynamics of various cottonwood genotypes, stand densities, stand management alternatives, and site productivity. However, demand from the C economy has already led to private refinement and wide-scale implementation of this plantation approach for the production of verifiable forestry C offsets and renewable biomass feedstock supplies [165].

Additional research on dedicated energy crop systems for farmed bottomlands was initiated in 2011 to analyze the costs and benefits associated with a range of production system alternatives [35]. The study, established near Hollandale,

MS, in the MAV (Fig. 1), examines four planting densities and associated harvest regimes of eastern cottonwood, including: (1) 10,127 trees ha<sup>-1</sup> with harvests in years 2, 4, 6, 8, and 10; (2) 6147 trees ha<sup>-1</sup> with harvests in years 4, 7, and 10; (3) 1993 trees ha<sup>-1</sup> with thinning in year 3 followed by complete harvest with reestablishment in year 5; and (4) 745 trees ha<sup>-1</sup> with harvest in year 10 [35]. Initial measurements on tree establishment and growth, biomass accumulation, and soil respiration are being analyzed to gain an understanding of how plantation density and harvest regime impact biomass yields and C balance on farmed bottomlands in the MAV [61].

### North Central Region

Aboveground C storage potential is currently being tested from the 10- and 20-year-old trees ( $n = 198$ ) belonging to the ecosystem services network defined in the biomass section above (Fig. 2). During felling, cross-sectional disks were harvested from each bole at 1.4-m height (i.e., DBH), 1/3 height of the tree, and 2/3 height of the tree. The disks were oven-dried at 55 °C until constant mass. One cross-sectional area of each disk was sanded and the sanded disks were then cut in half along a plane extending through the pith. A wafer, free of bark and defects, was cut from one half-disk and sanded. For each tree, three subsamples were collected from each growth ring from each positional cross-sectional disk, resulting in approximately 25,000 samples for analyses. Samples were analyzed for total C using a Flash EA1112 N-C analyzer (Thermo Electron, via CE Elantech, Inc., Lakewood, NJ) with a model MAS 200 autosampler. Data analyses are currently underway. In summary, the C concentrations of individual samples ranged from 40.1 to 52.8 %, with an overall mean of 47.2 %. For the 10-year-old trees, clone means ranged from 46.8 % ('C916000'; *P. deltoides* × *P. deltoides*) to 48.5 % ('NM2'; *P. nigra* × *P. suaveolens* subsp. *maximowiczii*). For the 20-year-olds, clone 'DN34' (*P. deltoides* × *P. nigra*) exhibited a mean C concentration of 47.4 %, while 'DN182' (*P. deltoides* × *P. nigra*) had 47.2 %, on average. Stand-level C storage across genotypes and sites of the 10-year-olds ranged from 1.5 to 8.0 Mg C ha<sup>-1</sup> year<sup>-1</sup> (mean = 4.2 Mg C ha<sup>-1</sup> year<sup>-1</sup>), while values for the older stands were 1.9–10.2 Mg C ha<sup>-1</sup> year<sup>-1</sup> (mean = 5.5 Mg C ha<sup>-1</sup> year<sup>-1</sup>) [36]. Depending on specific genotype × environment interactions, these results have substantial ecological and economic practical implications when compared to the commonly accepted value of C comprising 50 % of wood [166]. For example, at 10 years after planting, the Birdsey [166] estimate would overestimate the mean C storage potential of all clones by 3–6 %, regardless of where they were grown. Given the broad genetic variability within the genus *Populus* [167–169], generalizations for many traits should be used with caution, and this is certainly true for C.

## Water

### Hybrid Poplar

Chemical analysis of stable isotope ratios in tree growth rings has been proven useful in evaluating water use efficiency (WUE) in trees [170], as previous research has demonstrated for various species including poplars and their hybrids [171–173]. Despite the importance of this information for species and genotype selection in the face of changing climates, a limited amount of information exists for hybrid poplar in the USA. Therefore, as part of the ecosystem services network described above (Fig. 2), the WUE of seven clones of 10-year-old hybrid poplars is being evaluated at three sites in the North Central USA. The overarching objective is to identify genotypes with high WUE that are less susceptible to water stress compared to those with low WUE [174], thereby increasing the biomass yield potential on drier and/or water-limited sites [172]. Wood samples from annual growth rings were collected from the carbon wafers described above (i.e., carbon section) and analyzed for carbon isotope composition ( $\delta^{13}\text{C}$ ). These  $\delta^{13}\text{C}$  data are being analyzed to test for significant differences attributed to three genomic groups [*P. deltoides* (pure species); (*P. trichocarpa* × *P. deltoides*) × *P. deltoides* (first-generation backcross hybrids); and *P. nigra* × *P. suaveolens* subsp. *maximowiczii* (F<sub>1</sub> hybrid commercial control)] (and, separately, genotypes), sites, and their interactions. In addition, the  $\delta^{13}\text{C}$  data are being evaluated together as covariates with climate and soil variables to further improve our understanding of how genotype-specific WUE interacts with site conditions to impact biomass yields and associated ecosystem services. Preliminary data indicate that the sites differed in terms of water stress, as general trends in  $\delta^{13}\text{C}$  levels were apparent across sites and were consistent across genotypes. The results also suggest the potential for genetic selection based on WUE, as several genotypes exhibited stable or increased growth rates under elevated water stress (high WUE), whereas others exhibited reduced growth under such conditions (Headlee et al., unpublished data).

### Eucalypts

Water use of eucalypts has been a controversial issue internationally [175], and much has been made of the effect of converting other land uses to *Eucalyptus* plantations. Eucalypts have potentially higher water use and WUE compared to pasture, pine plantations, and native forests. In addition, WUE is a major determinant of productivity [175]. Water use at the individual tree and stand levels varies significantly among *Eucalyptus* clones and is not a constant characteristic of a given genotype, but overall, eucalypts have similar WUE to other tree species. Water consumption at the stand level depends upon water availability and vapor pressure deficit.

Actual water use by eucalypts in a watershed depends on many factors including the areal extent, size, spatial distribution, productivity, and age-class distribution of planted stands. Studies in other countries suggest that water consumption by *Eucalyptus* plantations will be higher in terms of percentage of water supply in drier regions, but absolute water consumption will be higher in wetter regions [175].

Ongoing modeling studies are examining the potential water use of expanded *Eucalyptus* plantations in the South at the tree, stand, and watershed levels. Ouyang et al. [176] modeled hydrological processes and water use in a *E. urophylla* plantation. They examined the potential impacts on water use of wet and dry sandy soil conditions. The maximum rate of leaf transpiration was about five times greater than that of soil evaporation. The cumulative annual water use by the eucalypts was 3200 L tree<sup>-1</sup>. Vose et al. [177] focused on water yield (*Q*) at the stand and the regional scales (12-digit Hydrologic Unit Code watershed) in the Lower Coastal Plain of the South where there is potential to expand freeze-tolerant eucalypt plantations [8]. They found that at the stand level, the *Q* for *Eucalyptus* was comparable to some pine plantations or slightly reduced by 9–16 % of precipitation (1300 mm year<sup>-1</sup>). This occurred at a leaf area index (LAI) of 4. Greater reduction in *Q* occurred at higher productivity levels, by as much as 500 mm year<sup>-1</sup> (a reduction of 33–63 % of precipitation) when the LAI was 5.

These studies suggest that predicted watershed-level response to small and moderate amounts of land in *Eucalyptus* plantations in the Southern USA may be difficult to detect. Economic analysis indicates a 20 % conversion of conifer to frost-tolerant eucalypts [8]. At this scale of conversion, reductions in water yield at the 12-digit HUC scale will be negligible. The variability in WUE among *Eucalyptus* clones suggests a potential for breeding trees with improved WUE and drought resistance, which could be important under future climate and land uses that compete with forestry for available water.

### Mixed Species

Recent joint USDA FS–USDA Agricultural Research Service (USDA ARS) partnerships extend beyond the scope of the USA and North America. The USDA FS International Programs (<http://www.fs.fed.us/about-agency/international-programs>) has collaborated with the USAID Mission in Cairo, Egypt, where the water resource is arguably the most important ecosystem service. In short, since 2004, Egypt has been developing wastewater reuse strategies for non-edible crops (including trees grown along rural to urban gradients) because they will not be able to meet the increasing water demand from the Nile River, which supplies the country with almost 97 % of its freshwater. Given the treaties with Sudan, Egypt is limited to 55.5 billion m<sup>3</sup> of Nile freshwater annually.



Following the establishment of 24 forests designed to irrigate the trees with treated wastewater, a joint USDA FS–USDA ARS technical assistance team evaluated the feasibility of scaling up similar afforestation projects in the country. In addition to the final report, the team evaluated strategies for afforestation [178] and irrigation [179]. Six suitable tree genera were identified based on soil characteristics and water quality/quantity issues: (1) *Populus*, *Pinus*, and *Eucalyptus* for pulpwood or sawnwood (versatile species); (2) *Khaya* (mahogany) and *Tectona* (teak) for high-value products; and (3) *Gmelina* (beechwood) for pulpwood [178]. Water quality was a major component of the recommended silvicultural prescriptions for successful biomass production using treated wastewater outside of the Nile Delta. Two overarching concerns for water quality improvement were identified: (1) mitigating return flow of treated wastewater back into Nile surface waters and its tributaries and (2) mitigating deep percolation losses into the alluvial aquifer as a result of irrigating the sandy delta soils. Using the trees as filters to reduce subsurface movement of nitrogen, phosphorus, and other potential pollutants (e.g., heavy metals, salts) was also a consideration for water quality improvements following irrigation [178]. To address these collective concerns, Evett et al. [179] developed irrigation strategies based on species' water use requirements, climate, and soil conditions. Given the high water use of *Populus*, one pertinent outcome that can be applied to North American poplar production systems is the potential increase in irrigation frequency in order to meet the trees' water requirements without sustaining the aforementioned deep percolation losses and subsequent aquifer contamination [179], especially in phytoremediation systems as described in Zalesny et al. [94] of this special issue.

## Soils and Wildlife Habitat Restoration

Soil protection and establishment of forest habitats for wildlife are central thrusts of USDA conservation easement programs available to owners of agricultural land. The infrastructure of large-scale, forest restoration research established on the Sharkey Restoration Research and Demonstration Site (Fig. 1) has provided opportunity to examine soil development and the development of forest habitats and wildlife use in short-rotation eastern cottonwood plantations. Pre-restoration measurement of soil variables including carbon, nutrients, and bulk density enables future study of the trajectory of soil recovery from agriculture [37]. Initial measurements from the surface (0–7.5 cm) illustrated a 31 % loss in soil N and a 33 % loss in soil carbon on this degraded agricultural site [37]. At year 5, foliar N levels in eastern cottonwood were substantially lower than the levels required for optimal biomass production, revealing persistence of soil nutrient depletion during early forest restoration [180]. Other

ecosystem functions responded more rapidly to the establishment of eastern cottonwood forest cover. Hamel [181], who studied winter bird use, reported that avian communities in 4- to 6-year-old eastern cottonwood stands held twice as many species as communities in stands of slower-growing hardwoods. He concluded that the fast vertical growth of eastern cottonwood stands, such as those established for bioenergy purposes, facilitates a more rapid assembly of forest canopy birds than stands of slower-growing trees [181]. Research conducted to date supports the premise that biomass plantations can play a role in the restoration and conservation of biodiversity, particularly within landscapes such as the MAV which is dominated by agricultural land use.

## Research to Advance Other Genera

Efforts to develop SRWC systems in the Southern USA have brought significant focus on plantation culture of several species not previously covered in this manuscript. These efforts were generally initiated to develop alternative plantation options for addressing particular site requirements, producing desirable fiber or feedstock qualities, or providing for particular ecosystem services not offered by conventional plantation species. American sycamore (*Platanus occidentalis* L.), sweetgum, yellow poplar (*Liriodendron tulipifera* L.), black locust (*Robinia pseudoacacia* L.), and green ash are among the trees that have been investigated for plantation culture because of their potential as alternatives to the currently utilized plantation species [12, 182, 183]. Three broadleaf species—American sycamore, sweetgum, and black willow (*Salix nigra* Marshall)—are currently being studied by the USDA FS Southern Research Station because they hold a strong potential for future use in woody crop feedstock production systems in the Southern USA.

## American Sycamore and Sweetgum

For many decades, forest industry championed University of Georgia and USDA FS research on American sycamore fiber and feedstock production. This species demonstrates high productivity on a wide range of upland and bottomland sites, it has favorable pulping properties, and its biology is amenable to intensive silviculture (i.e., it can be propagated from stem cuttings and can be coppiced over several rotations) [12, 184]. This research investment led to substantial gains in appropriate silvicultural practices, plantation system management, and productivity [12].

In the southeastern USA, the growth and productivity of sycamore and sweetgum grown with a range of water and nutrient availability were evaluated in two separate experiments on the Upper Coastal Plain of South Carolina. After 8 years, Coyle et al. [28] found that the optimal fertilization

rates were 147 and 141 kg N ha<sup>-1</sup> year<sup>-1</sup> for irrigated and non-irrigated sycamore, respectively. The productivity of sycamore receiving irrigation was 6.5 dry Mg aboveground woody biomass per hectare per year, a 20 % increase over the biomass production rate without irrigation. In contrast, the optimal fertilization rates for sweetgum differed with (85 kg N ha<sup>-1</sup> year<sup>-1</sup>) and without (111 kg N ha<sup>-1</sup> year<sup>-1</sup>) irrigation. The aboveground woody biomass of sweetgum was 52 % greater with compared to without irrigation.

A concurrent study examined sycamore and sweetgum growth and productivity in a 2 × 2 factorial experiment with and without irrigation and fertilization (0 or 120 kg N ha<sup>-1</sup> year<sup>-1</sup>) [27]. After nine growing seasons, sycamore responded significantly to both irrigation and fertilization, as aboveground woody biomass productivity in trees receiving irrigation and fertilization was 8.6 dry Mg ha<sup>-1</sup> year<sup>-1</sup>; productivity was 219 % greater compared to trees that received no resource amendments (i.e., control) [30]. Sweetgum productivity was 21.3 dry Mg ha<sup>-1</sup> year<sup>-1</sup> in irrigated and fertilized treatments after 11 growing seasons, and this rate was 344 % greater than trees in the control plots [30]. After accounting for tree size, the proportion of belowground biomass was not affected by resource availability in sycamore, but decreased as resource availability increased in sweetgum.

In spite of these positive gains, wide-scale use of American sycamore in plantation culture has been impeded by chronic disease problems [87]. Particularly problematic is the endemic xylem disease bacterial leaf scorch, which is caused by the pathogen *Xylella fastidiosa* Wells et al. and is transmitted to American sycamore by a xylem-feeding insect, the glassy-winged sharpshooter (*Homalodisca vitripennis* Germar) [185]. Upon infection of the host, colonization of xylem vessels by the bacterium leads to dysfunction of the vascular system and water stress that results in leaf scorching, foliage dieback, and tree decline [186]. Plantations in the Southern USA are typically symptomatic a few years after establishment, with progression to mortality within 5–7 years [187, 188].

Ongoing research is focused on traditional tree breeding to address the bacterial leaf scorch issue. Adams et al. [67] identified American sycamore families that exhibit resistance to bacterial leaf scorch and demonstrated that breeding for disease resistance can substantially decrease symptoms. Concurrent investigation into the mechanism of disease resistance indicates that the concentrations of certain glycosides with known bactericidal efficacy on *X. fastidiosa* vary considerably among American sycamore families (Leininger, personal communication). Indeed, glycoside concentration in sycamore leaves was positively correlated with healthy, asymptomatic trees (Leininger, personal communication). In the future, American sycamore could account for a greater role in biomass feedstock production if the breeding program currently focused on disease resistance is successful in producing cultivars suitable for deployment.

## Black Willow

Willows, particularly shrub willows, have gained prominent use in short-rotation applications in several regions of the world [189]. Black willow is a fast-growing tree species that is endemic to alluvial forests throughout much of the Eastern USA. This species exhibits relatively high productivity on wet alluvial sites, is readily propagated through vegetative reproduction, and can be regenerated through coppicing. For these reasons, researchers have long recognized the potential of black willow for genetic improvement and use as a biomass species [190, 191], but this potential has not resulted in a sustained effort to forward the species for plantation culture. The current emphasis on the development of sustainable alternatives for biomass feedstock production and the availability of alluvial land that is marginal for agricultural production have created an opportunity for the development of black willow as a plantation species [35, 58].

The USDA FS has initiated collaboration with researchers at other organizations, including Mississippi State University and Louisiana Tech University, in an effort to advance black willow as an alternative plantation species for use on marginal agricultural land in alluvial floodplains. Initial and ongoing research primarily addresses the development of sustainable plantation systems and tree improvement. Experiments designed to provide reliable planting stock and propagation techniques [62], inform pest management practices [63], delineate planting densities and rotation lengths that optimize productivity [35], quantify carbon and nutrient life cycle dynamics [61], and refine harvesting practices [38] are providing the foundation for the development of sustainable black willow plantation systems. Equally vital to sustainability is the implementation of a tree improvement program that can produce genetically superior cultivars suitable for operational deployment into dedicated biomass plantations on alluvial soils [58]. In 2009, researchers began collecting genotypes from selected geographical sources and established cutting orchards to replicate the genotypes for intensive trials. Replicated clonal screening trials, early-age selection, and clonal refinement tests on material from 10 geographic areas are demonstrating significant geographic source and clone variation [59, 60]. Ongoing screening trials and refinement tests will identify the best-performing clones for increased gain and eventually selection of superior genotypes for the production of biomass on marginal agricultural land.

## Future Research Directions

Four areas of continuing research are in progress to further advance biomass, carbon, water, and soil research.

1. Integrate energy, climate, and tree genetics to test the physiological and environmental effects on biomass, bioenergy, soil health, erosion control, and water quality and quantity.
2. Develop quantitative genetic models to predict the outcome of genotype  $\times$  environment interactions as they affect limits to the geographic transfer of clonal selections and the design of environmental technologies, including phytoremediation.
3. Develop silvicultural guidelines for the establishment and growth of short-rotation woody crops, with special emphasis on genetic and environmental effects on rooting.
4. Enhance regional and national feedstock resource assessments and economic analyses to integrate biomass productivity models with carbon sequestration throughout the energy supply chain.

Four areas of continuing research are in progress to further extend BioSAT.

1. BioSAT for Kansas. The primary goal is to create a web-accessible model for Kansas and its border states (i.e., Nebraska, Iowa, Missouri, Arkansas, and Oklahoma) to evaluate agricultural, range, and forest locations for sustainable biomass facilities.
2. Suitability indices for Washington, Oregon, Idaho, and Montana in the Context of BioSAT. The goals are to (a) create new tools that enable complex interactions within the operations of the biomass supply chains to be studied and refined and (b) facilitate a sustainable supply chain for alternative aviation fuels using geospatial suitability overlays to screen for biomass production, secondary data collection, and strategic analysis (e.g., key features of the BioSAT model—land features and socioeconomic factors).
3. Next-generation logistics systems for delivering optimal biomass feedstocks to biorefining industries in the southeastern USA utilizing BioSAT. The goals are to (a) develop and demonstrate a state-of-the-art biomass merchandising and processing depot to identify and reduce sources of variation along the supply chain of multiple high-impact biomass sources (loblolly pine and switchgrass) and (b) develop practices that manage biomass variability to deliver a consistent feedstock optimized for performance in specific technology platforms.
4. Natural Disaster Vulnerability Index (NDVI) in the context of BioSAT. The primary goal is to integrate a spatially explicit NDVI into the current web-based BioSAT system, wherein vulnerability refers to different variables that make biomass-using facilities less able to absorb the impact and recover from a disaster event [192, 193]. This research is important for improving biomass and bioenergy analysis by integrating risk visualization to help

recognize and reduce risk from potential natural disasters for small-scale biomass supply chain operations.

**Acknowledgments** The majority of the research described in this paper was supported by the USDA Forest Service as collaborations associated with the USDA Biomass Research Centers. In addition to agency colleagues, we are grateful to the many external partners who made these collective efforts possible and to the countless number of people who helped us with laboratory, greenhouse, and field work. Furthermore, we thank Dr. Marilyn Buford for her USDA Forest Service leadership, Sue Lietz for producing Fig. 1, and Edmund Bauer and Max Piana for reviewing earlier versions of this manuscript.

## References

1. Mendel BC, Lang AJ (2012) Wood for bioenergy: forests as a resource for biomass and biofuels. Forest History Society, Durham, NC, 68 pp
2. EIA (Energy Information Administration) (2011) History of energy consumption in the United States, 1775–2009. Washington, DC. Accessed 29 September 2015. <http://www.eia.gov/todayinenergy/detail.cfm?id=10#>
3. Society of American Foresters (1979) Forest biomass as an energy source. Study Report of a Task Force of the Society of American Foresters. Society of American Foresters, Washington, DC, 7 pp
4. Inman RE (1977) Silvicultural biomass farms. Vol 1 summary. MITRE Corporation, McLean, VA, 62 pp
5. EIA (Energy Information Administration) (2015) History of energy consumption in the United States, 1775–2009. Washington, DC. Accessed 29 September 2015. <http://www.eia.gov/todayinenergy/detail.cfm?id=10#>
6. US Department of Energy (2011) US Billion-Ton Update: Biomass supply for a bioenergy and bioproducts industry. Perlack RD, Stokes BJ (Leads). ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN, 227 pp
7. Stoof CR, Richards BK, Woodbury PB, Fabio ES, Brumbach AR, Chemej J, Das S, Geohrig L, Hansen J, Hornesky J, Mayton H, Mason C, Ruestow G, Smart LB, Volk TA, Steenhuis TS (2015) Untapped potential: opportunities and challenges for sustainable bioenergy production from marginal lands in the Northeast USA. *BioEnergy Res* 8:482–501
8. Wear DN, Abt RC, Dixon E IV, Singh N (2015) Projecting potential adoption of genetically engineered freeze-tolerant *Eucalyptus* in the United States. *For Sci* 61:466–480
9. Zalesny RS Jr, Donner DM, Coyle DR, Headlee WL (2012) An approach for siting poplar energy production systems to increase productivity and associated ecosystem services. *For Ecol Manag* 284:45–58
10. Dickmann DI (2006) Silviculture and biology of short-rotation woody crops in temperate regions: then and now. *Biomass Bioenergy* 30:696–705
11. McAlpine RG, Brown CL, Herrick AM, Ruark HE (1966) Silage sycamore. *For Farmer* 26:6–7
12. Steinbeck K (1999) Thirty years of short-rotation hardwoods research. In: Haywood JD (ed) Proceedings of the Tenth Biennial Southern Silvicultural Research Conference, 16–18 February 1999, Shreveport, LA. Gen Tech Rep SRS-30. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 63–65 (618 pp)
13. Steinbeck K, McAlpine RG, May JT (1972) Short rotation culture of sycamore: a status report. *J For* 70:210–213



14. DeBell DS, Clendenen GW, Zasada JC (1993) Growing *Populus* biomass: comparison of woodgrass versus wider-spaced short-rotation systems. *Biomass Bioenergy* 4:305–313
15. Volk TA, Verwijst T, Tharakan PJ, Abrahamson LP, White EH (2004) Growing fuel: a sustainability assessment of willow biomass crops. *Front Ecol Environ* 2:411–418
16. Pillsbury NH, Ayers NL (1983) Establishing a *Eucalyptus* energy plantation on the central coast of California. In: Standiford RB, Ledig FT (tech coord). Proceedings of a Workshop on *Eucalyptus* in California, 14–16 June 1983, Sacramento, CA. Gen Tech Rep PSW-69. US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, pp 86–89
17. Schubert TH, Whitesell CD (1985) Species trials for biomass plantations in Hawaii: a first appraisal. Res Pap PSW-176. US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, 13 pp
18. Geyer WA, Melichar MW (1986) Short-rotation forestry research in the United States. *Biomass* 9:125–133
19. Vance ED, Loehle C, Wigley TB, Weatherford P (2014) Scientific basis for sustainable management of *Eucalyptus* and *Populus* as short-rotation woody crops in the U.S. *Forests* 5:901–918
20. Hinchey M, Zhang C, Chang S, Cunningham M, Hammond W, Nehra N (2011) Biotech Eucalyptus can sustainably address society's need for wood: the example of freeze tolerant *Eucalyptus* in the southeastern US. *BMC Proceedings* 5:124. doi: 10.1186/1753-6561-5-S7-124
21. Zalesny RS Jr, Cunningham MW, Hall RB, Mirck J, Rockwood DL, Stanturf JA, Volk TA (2011) Woody biomass from short rotation energy crops (Ch 2). In: Zhu JY (ed) Sustainable production of fuels, chemicals, and fibers from forest biomass. ACS Symposium Series. American Chemical Society, Washington, DC, pp 27–63
22. Zalesny RS Jr, Hall RB, Zalesny JA, McMahon BG, Berguson WE, Stanosz GR (2009) Biomass and genotype × environment interactions of *Populus* energy crops in the Midwestern United States. *BioEnergy Res* 2:106–122
23. Riemenschneider DE, Berguson WE, Dickmann DI, Hall RB, Isebrands JG, Mohn CA, Stanosz GR, Tuskan GA (2001) Poplar breeding and testing strategies in the north-central U.S.: demonstration of potential yield and consideration of future research needs. *For Chron* 77:245–253
24. Headlee WL, Zalesny RS Jr, Hall RB, Bauer EO, Bender B, Birr BA, Miller RO, Randall JA, Wiese AH (2013) Specific gravity of hybrid poplars in the north-central region, USA: within-tree variability and site × genotype effects. *Forests* 4:251–269
25. Coyle DR, Coleman MD, Durant JA, Newman LA (2006) Survival and growth of 31 *Populus* clones in South Carolina. *Biomass Bioenergy* 30:750–758
26. Kaczmarek DJ, Coyle DR, Coleman MD (2013) Survival and growth of a range of *Populus* clones in central South Carolina USA through age ten: do early assessments reflect longer-term survival and growth trends? *Biomass Bioenergy* 49:260–272
27. Coleman MD, Coyle DR, Blake J, Britton K, Buford M, Campbell B, Cox J, Cregg B, Daniels D, Jacobson M, Johnson K, McDonald T, McLeod K, Nelson E, Robison D, Rummer R, Sanchez P, Stanturf J, Stokes B, Trettin C, Tuskan J, Wright L, Wullschlegel S (2004) Production of short rotation woody crops grown with a range of nutrient and water availability: establishment report and first-year responses. SRS-GTR-072. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 21 pp
28. Coyle DR, Aubrey DP, Siry JC, Volfovic-Leon RR, Coleman MD (2013) Optimal nitrogen application rates for three intensively-managed hardwood tree species in the southeastern USA. *For Ecol Manag* 303:131–142
29. Coyle DR, Coleman MD (2005) Forest production responses to irrigation and fertilization are not explained by shifts in allocation. *For Ecol Manag* 208:137–152
30. Coyle DR, Aubrey DP, Coleman MD (2016) Growth responses of narrow or broad site adapted tree species to a range of resource availability treatments after a full harvest rotation. *For Ecol Manag* 362:107–119
31. Coyle DR, Coleman MD, Aubrey DP (2008) Above and below-ground biomass accumulation, production, and distribution of sweetgum and loblolly pine grown with irrigation and fertilization. *Can J For Res* 38:1335–1348
32. Coyle DR, Nebeker TE, Hart ER, Mattson WJ Jr (2005) Biology and management of insect pests in North American intensively-managed hardwood forest systems. *Annu Rev Entomol* 50:1–29
33. Coyle DR (2002) Effects of clone, silvicultural, and miticide treatments on cottonwood leafcurl mite (Acari: Eriophyidae) damage in plantation *Populus*. *Environ Entomol* 31:1000–1008
34. Coyle DR, Coleman MD, Durant JA, Newman LA (2006) Multiple factors affect pest and pathogen damage on 31 *Populus* clones in South Carolina. *Biomass Bioenergy* 30:759–768
35. Souter RA, Gardiner ES, Leininger TD, Mitchell D, Rummer RB (2015) Eastern cottonwood and black willow biomass crop production in the Lower Mississippi Alluvial Valley under four planting densities. In: Gordon HA, Connor KF, Haywood JD (eds). Proceedings of the 17th Biennial Southern Silvicultural Research Conference. e-Gen Tech Rep SRS-203. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 340–342 (551 pp)
36. Zalesny RS Jr, Headlee WL (2015) Developing woody crops for the enhancement of ecosystem services under changing climates in the North Central United States. *J For Exp Sci* 31:78–90
37. Stanturf JA, Gardiner ES, Shepard JP, Schweitzer CJ, Portwood CJ, Dorris LC Jr (2009) Restoration of bottomland hardwood forests across a treatment intensity gradient. *For Ecol Manag* 257:1803–1814
38. de Souza DPL, Gallagher T, Mitchell D, Smidt M, McDonald T, Wright J (2014) Determining the impact of felling method and season of year on coppice regeneration. In: Proceedings of the Global Harvesting Technology 2014, Council on Forest Engineering Annual Meeting, 22–25 June 2014, Moline, IL, 6 pp
39. Zalesny JA, Zalesny RS Jr, Wiese AH, Hall RB (2007) Choosing tree genotypes for phytoremediation of landfill leachate using phyto-recurrent selection. *Int J Phytoremed* 9:513–530
40. Bañuelos GS, LeDuc D, Johnson J (2010) Evaluating the tolerance of young hybrid poplar trees to recycled waters high in salinity and boron. *Int J Phytoremed* 12:419–439
41. Mahama AA, Hall RB, Zalesny RS Jr (2011) Differential interspecific incompatibility among *Populus* hybrids in sections *Aigeiros* Duby and *Tacamahaca* Spach. *Forestry Chron* 87:790–796
42. Zalesny RS Jr, Hallett RA, Falxa-Raymond N, Wiese AH, Birr BA (2014) Propagating native Salicaceae for afforestation and restoration in New York City's five boroughs. *Native Plants J* 15:29–41
43. Zalesny RS Jr, Headlee WL, Gopalakrishnan G, Bauer EO, Hall RB, Hazel DW, Isebrands JG, Licht LA, Negri MC, Guthrie-Nichols E, Rockwood DL, Wiese AH (2015) Long-term monitoring of poplars used for phytoremediation. 12th International Conference of the International Phytotechnology Society: Phytotechnologies for Sustainable Development. 27–30 September 2015, Manhattan, Kansas
44. Zalesny RS Jr, Wiese AH (2006) Date of shoot collection, genotype, and original shoot position affect early rooting of dormant hardwood cuttings of *Populus*. *Silvae Genet* 55:169–182
45. Headlee WL, Zalesny RS Jr, Donner DM, Hall RB (2013) Using a process-based model (3-PG) to predict and map hybrid poplar

- biomass productivity in Minnesota and Wisconsin, USA. *BioEnergy Res* 6:196–210
46. Netzer DA, Tolsted D, Ostry ME, Isebrands JG, Riemenschneider DE, Ward KT (2002) Growth, yield, and disease resistance of 7- to 12-year-old poplar clones in the North Central United States. Gen Tech Rep NC-229. US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, 31 pp
47. Wang ZJ, Zhu JY, Zalesny RS Jr, Chen KF (2012) Ethanol production potential from poplar wood through enzymatic saccharification and fermentation. *Fuel* 95:606–614
48. Zhang J, Gu F, Zhu JY, Zalesny RS Jr (2015) Using a combined hydrolysis factor to optimize high titer ethanol production from sulfite-pretreated poplar without detoxification. *Biores Technol* 186:223–231
49. Bañuelos GS, Shannon MC, Ajwa H, Draper JH, Jordahl J, Licht L (1999) Phytoextraction and accumulation of boron and selenium by poplar (*Populus*) hybrid clones. *Int J Phytoremed* 1:81–96
50. Shannon MC, Bañuelos GS, Draper JH, Ajwa H, Jordahl J, Licht L (1999) Tolerance of hybrid poplar (*Populus*) trees irrigated with varied levels of salt, selenium, and boron. *Int J Phytoremed* 1:273–288
51. Zalesny RS Jr, Riemenschneider DE, Hall RB (2005) Early rooting of dormant hardwood cuttings of *Populus*: analysis of quantitative genetics and genotype  $\times$  environment interactions. *Can J For Res* 35:918–929
52. Rees R, Robinson BH, Menon M, Lehmann E, Guenthardt-Georg MS, Schulin R (2012) Boron accumulation and toxicity in hybrid poplars (*P. nigra*  $\times$  *euramericana*). *Environ Sci Technol* 45:10538–10543
53. Smesrud JK, Duvendack GD, Obreiner JM, Jordahl JL, Madison MF (2012) Practical salinity management for leachate irrigation to poplar trees. *Int J Phytoremed* 14:26–46
54. Zalesny RS Jr, Bauer EO, Riemenschneider DE (2004) Use of belowground growing degree days to predict rooting of dormant hardwood cuttings of *Populus*. *Silvae Genet* 53:154–160
55. Headlee WL, Hall RB, Zalesny RS Jr (2013) Establishment of alleycropped hybrid aspen "Crandon" in Central Iowa, USA: effects of topographic position and fertilizer rate on aboveground biomass production and allocation. *Sustainability* 5:2874–2886
56. Wiese AH, Zalesny JA, Donner DM, Zalesny RS Jr (2006) Bud removal affects shoot, root, and callus development of hardwood *Populus* cuttings. *Silvae Genet* 55:141–148
57. Zalesny RS Jr, Bauer EO (2007) Evaluation of *Populus* and *Salix* continuously irrigated with landfill leachate I. Genotype-specific elemental phytoremediation. *Int J Phytoremed* 9:281–306
58. Rousseau RJ, Gardiner ES, Leininger TD (2012) Development of an applied black willow tree improvement program for biomass production in the South. In: Butnor JR (ed) Proceedings of the 16th Biennial Southern Silvicultural Research Conference. e-Gen Tech Rep SRS-156. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 273–277 (391 pp)
59. Rousseau RJ, Leininger TD, Herrin BL, Gardiner ES (2013) Evaluating the potential of black willow as a viable biomass species for the LMAV. In: Cunningham MW (ed) Proceedings of the 32nd Southern Forest Tree Improvement Conference, 10–13 June 2013, Clemson, SC, pp 61–63 (113 pp)
60. Bailey RB, Rousseau RJ, Gardiner E, Mack JC (2014) Black willow tree improvement: development of a biomass species for marginal agricultural land in the Lower Mississippi Alluvial Valley. In: Groninger JW, Holzmueller EJ, Nielsen CK, Dey DC (eds) Proceedings of the 19th Central Hardwood Forest Conference. Gen Tech Rep NRS-P-142. US Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, pp 263–264 (388 pp)
61. Hood WG, Tyree MC, Dillaway DN, Leininger TD (2015) Measuring and partitioning soil respiration in Sharkey shrink-swell clays under plantation grown short-rotation woody crops. In: Gordon HA, Connor KF, Haywood JD (eds) Proceedings of the 17th Biennial Southern Silvicultural Research Conference. e-Gen Tech Rep SRS-203. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 318–320 (551 pp)
62. Camp JC, Rousseau RJ, Gardiner ES (2012) Longer black willow cuttings result in better initial height and diameter growth in biomass plantations. In: Butnor JR (ed) Proceedings of the 16th Biennial Southern Silvicultural Research Conference. e-Gen Tech Rep SRS-156. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 43–46 (391 pp)
63. Fernandes LDS, Souter RA, Leininger TD (2015) Evaluating growth effects from an imidacloprid treatment in black willow and eastern cottonwood cuttings. In: Gordon HA, Connor KF, Haywood JD (eds) Proceedings of the 17th Biennial Southern Silvicultural Research Conference. e-Gen Tech Rep SRS-203. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 281–282 (551 pp)
64. Coyle DR, Nowak JT, Fettig CJ (2003) Irrigation and fertilization effects on Nantucket pine tip moth (Lepidoptera: Tortricidae) damage levels and pupal weight in an intensively-managed pine plantation. *J Entomol Sci* 38:621–630
65. Hall RB (2008) Woody bioenergy systems in the United States. In: Zalesny RS Jr, Mitchell R, Richardson J (eds) Biofuels, bioenergy, and bioproducts from sustainable agricultural and forest crops: Proceedings of the Short Rotation Crops International Conference, 18–22 August 2008, Bloomington, MN. Gen Tech Rep NRS-P-31. US Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA, p 18 (76 pp)
66. Coyle DR, Aubrey DP, Bentz J (2010) *Erythroneura lawsoni* (Homoptera: Cicadellidae) abundance and feeding injury levels are influenced by foliar nutrient status in intensively managed American sycamore. *Agric For Entomol* 12:89–97
67. Adams JP, Rousseau RJ, Leininger TD (2012) Genetic control of growth traits and inheritance of resistance to bacterial leaf scorch in American sycamore. *Silvae Genet* 61:198–206
68. Stanton BJ, Serapiglia MJ, Smart LB (2014) The domestication and conservation of *Populus* and *Salix* genetic resources (Ch 4). In: Isebrands JG, Richardson J (eds) Poplars and willows: trees for society and the environment. FAO and CABI, Rome, Italy, pp 124–199, 634 pp
69. Stanturf JA, van Oosten C (2014) Operational poplar and willow culture (Ch 5). In: Isebrands JG, Richardson J (eds) Poplars and willows: trees for society and the environment. FAO and CABI, Rome, Italy, pp 200–257, 634 pp
70. Kellison RC, Lea R, Marsh P (2013) Introduction of *Eucalyptus* spp. into the United States with special emphasis on the Southern United States. *Int J For Res* (article ID 189393, 9 pp). doi:10.1155/2013/189393
71. Stout AB, Schreiner EJ (1933) Results of a project in hybridizing poplars. *J Heredity* 24:216–219
72. Farmer RE Jr, Mohn CA (1970) Genetic improvement of eastern cottonwood. *Silviculture and Management of Southern Hardwoods*, Proceedings of the Louisiana State University 19th Annual Forestry Symposium, Baton Rouge, LA, pp 5–11
73. Maisenhelder LC (1970) Eastern cottonwood selections outgrow hybrids on southern sites. *J For* 68:300–301
74. Mohn CA, Randall WK, McKnight JS (1970) Fourteen cottonwood clones selected for mid-south timber production. Res Pap SO-62. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, 17 pp

75. Cooper DT (1979) Cottonwood culture and research in the South. Proc N Am Poplar Counc Annu Meet 1979:3–11
76. Johnson RL (1972) Genetically improved cottonwood: a research and development success. In: Proceedings of the 1972 National Convention, Society of American Foresters, Bethesda, MD, pp 113–119
77. McKnight JS (1970) Planting cottonwood cuttings for timber production in the South. Res Pap SO-60. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, 17 pp
78. US Department of Agriculture, Forest Service (1983) Energy and wood from intensively cultured plantations: research and development program. Gen Tech Rep NC-58. US Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN, 28 pp
79. Hansen EA, Ostry ME, Johnson WD, Tolsted DN, Netzer DA, Berguson WE, Hall RB (1994) Field performance of *Populus* in short-rotation culture plantations in the North-Central U.S. Gen Tech Rep NC-320. US Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN, 13 pp
80. Moore PW (1983) Southern California trial plantings of *Eucalyptus*. In: Standiford RB, Ledig FT (technical coord) Proceedings of a workshop on *Eucalyptus* in California, 14–16 June 1983, Sacramento, CA. Gen Tech Rep PSW-69. US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, pp 14–18
81. Sachs RM, Low CB (1983) Yields in high density, short rotation intensive culture (SRIC): plantations of *Eucalyptus* and other hardwood species. In: Standiford RB, Ledig FT (tech coord) Proceedings of a Workshop on *Eucalyptus* in California, 14–16 June 1983, Sacramento, CA. Gen Tech Rep PSW-69. US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, pp 71–75
82. Whitesell CD, DeBell DS, Schubert TH, Strand RF, Crabb TB (1992) Short-rotation management of *Eucalyptus*: guidelines for plantations in Hawaii. Gen Tech Rep PSW-GTR-137. US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 30 pp
83. Rockwood DL (2012) History and status of *Eucalyptus* improvement in Florida. Int J For Res 2012:1–10 (article ID 607879, 10 pp). doi:10.1155/2012/607879
84. Geary TE, Meskimen GF, Franklin EC (1983) Growing *Eucalyptus* in Florida for industrial wood production. Gen Tech Rep SE-23. US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, NC
85. Rockwood DL, Rudie AW, Ralph SA, Zhu JY, Winandy JE (2008) Energy product options for *Eucalyptus* species grown as short rotation woody crops. Int J Mol Sci 9:1361–1378
86. Gonzalez R, Wright J, Saloni D (2010) The business of growing *Eucalyptus* for biomass. Biomass Magazine 4:52–56
87. Kline KL, Coleman MD (2010) Woody energy crops in the southeastern United States: two centuries of practitioner experience. Biomass Bioenergy 34:1655–1666
88. Vance ED, Maguire DA, Zalesny RS Jr (2010) Research strategies for increasing productivity of intensively managed forest plantations. J For 108:183–192
89. Nelson CD, Peter GF, McKeand SE, Jokela EJ, Rummer RB, Groom LH, Johnsen KH (2013) Pines (Ch 20). In: Singh BP (ed) Biofuel crops: production, physiology and genetics. CABI, Wallingford, UK, pp 427–459, 548 pp
90. Munsell JF, Fox TR (2010) An analysis of the feasibility for increasing woody biomass production from pine plantations in the Southern United States. Biomass Bioenergy 34:1631–1642
91. Koch P (1980) Concept for southern pine plantation operations in the year 2020. J For 78:78–82
92. Scott DA, Tiarks A (2008) Dual-cropping loblolly pine for biomass energy and conventional wood products. South J Appl For 32:33–37
93. Albaugh JM, Sucre EB, Leggett ZH, Domec JC, King JS (2012) Evaluation of intercropped switchgrass establishment under a range of experimental site preparation treatments in a forested setting on the Lower Coastal Plain of North Carolina, USA. Biomass Bioenergy 46:673–682
94. Zalesny RS Jr, Stanturf JA, Gardiner ES, Bañuelos GS, Hallett RA, Hass A, Stange CM, Perdue JH, Young TM, Coyle DR, Headlee WL (2016) Environmental technologies of woody crop production systems. BioEnergy Res. doi:10.1007/s12155-016-9738-y
95. Millenium Ecosystem Assessment (MEA) (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, 155 pp
96. Goerndt ME, Mize C (2008) Short-rotation woody biomass as a crop on marginal lands in Iowa. North J Appl For 25:82–86
97. Johansson T, Karacic A (2011) Increment and biomass in hybrid poplar and some practical implications. Biomass Bioenergy 35: 1925–1934
98. Tuskan GA, Rensema TR (1992) Clonal differences in biomass characteristics, coppice ability, and biomass prediction equations among four *Populus* clones grown in eastern North Dakota. Can J For Res 22:348–354
99. Headlee WL, Zalesny RS Jr, Blazier MA, Liechty HO, Pelkki MH (2016) Development and comparison of aboveground woody biomass equations for improved poplars in the Upper- and Lower-Mississippi River regions. For Ecol Manag (in review)
100. Landsberg JJ, Waring RH, Coops NC (2003) Performance of the forest productivity model 3-PG applied to a wide range of forest types. For Ecol Manag 172:199–214
101. Amichev BY, Johnston M, Van Rees K (2010) Hybrid poplar growth in bioenergy production systems: biomass prediction with a simple process-based model (3PG). Biomass Bioenergy 34:687–702
102. Lazarus W, Headlee WL, Zalesny RS Jr (2015) Impacts of supplyshed-level differences in productivity and land costs on the economics of hybrid poplar production in Minnesota, USA. BioEnergy Res 8:231–248
103. Stanturf JA, van Oosten C, Netzer DA, Coleman MD, Portwood CJ (2001) Ecology and silviculture of poplar plantations (part A, Ch1). In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J (eds) Poplar culture in North America. NRC Research Press, National Research Council of Canada, Ottawa, ON, pp 153–206
104. Putnam J, McKnight JS, Furnival G (1960) Inventory and management of southern hardwoods. Agric Handbook 181. US Department of Agriculture, Forest Service, Washington Office, Washington, DC
105. Johnson RL, Burkhardt EC (1976) Natural cottonwood stands: past management and implications for plantations. In: Thielges BA, Land SB Jr (eds) Proceedings of the Symposium on Eastern Cottonwood and Related Species, 28 September–2 October 1976, Baton Rouge, LA, pp 20–30
106. Francis JK (1985) The roots of plantation cottonwood: their characteristics and properties. Res Note SO-314. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA
107. Krinard RM (1988) Volume equations for plantation cottonwood trees (*Populus deltoides*). Res Note SO-347. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA
108. Cao QV, Durand KM (1991) A growth and yield model for improved eastern cottonwood plantations in the Lower Mississippi Delta. South J Appl For 15:213–216



109. Cao QV, Durand KM (1991) Site index curves for eastern cottonwood plantations in the Lower Mississippi Delta. *South J Appl For* 15:28–30
110. Dowell RC, Gibbins D, Rhoads JL, Pallardy SG (2009) Biomass production physiology and soil carbon dynamics in short-rotation-grown *Populus deltoides* and *P. deltoides* × *P. nigra* hybrids. *For Ecol Manag* 257:134–142
111. Volk TA, Buford MA, Berguson W, Caputo J, Eaton J, Perdue JH, Rials TG, Biemenschneider D, Stanton B, Stanturf JA (2011a) Woody feedstocks: management and regional differences. In: Braun R, Karlen D, Johnson D (eds) Sustainable alternative feedstock opportunities, challenges and roadmap for six US regions. Proceedings of the Sustainable Feedstocks for Advance Biofuels Workshop, Soil and Water Conservation Society
112. Volk TA, Abrahamson LP, Cameron KD, Castellano P, Corbin T, Fabio E, Johnson G, Kuzovkina-Eischen Y, Labrecque M, Miller R, Sidders D (2011) Yields of willow biomass crops across a range of sites in North America. In: Booth E, Halford N, Sheild I, Taylor G, Turley D, Voigt T (eds) Aspects of applied biology 112. Biomass and bioenergy crops IV. Association of Applied Biologists, Warwick, UK, pp 67–74
113. Carter MC, Kellison RC, Wallinger RS (2015) Forestry in the U.S. South. Louisiana State University Press, Baton Rouge, LA, 448 pp
114. US Department of Agriculture, Forest Service (1929) Volume, yield and stand tables for second-growth southern pines. Misc. Publ. No. 50. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA
115. Wakeley PC (1954) Planting the southern pines. *Agric Mon* 18. US Government Printing Office, Washington, DC, 233 pp
116. Stanturf JA, Kellison RC, Broerman FS, Jones SB (2003) Innovation and forest industry: domesticating the pine forests of the Southern United States 1920–1999. *For Pol Econ* 5:407–419
117. Stanturf JA, Kellison RC, Broerman FS, Jones SB (2003) Productivity of southern pine plantations: where are we and how did we get here? *J For* 101:26–31
118. Fox TR, Allen HL, Albaugh TJ, Rubilar R, Carlson CA (2007) Tree nutrition and forest fertilization of pine plantations in the Southern United States. *South J Appl For* 31:5–11
119. Baldwin VC Jr, Feduccia DP (1987) Loblolly pine growth and yield prediction for managed West Gulf plantations. Res Paper SO-236. US Department of Agriculture, Forest Service, Northern Research Station, New Orleans, LA, 27 pp
120. Dean TJ, Baldwin VC (1996) Growth in loblolly pine plantations as a function of stand density and canopy properties. *For Ecol Manag* 82:49–58
121. Baldwin VC, Burkhardt HE, Westfall JA, Peterson KD (2001) Linking growth and yield and process models to estimate impact of environmental changes on growth of loblolly pine. *For Sci* 47: 77–82
122. Miller JH, Zutter BR, Zedaker M, Edwards MB, Newbold RA (2003) Growth and yield relative to competition control for loblolly pine plantations to midrotation: a southeastern United States regional study. *South J Appl For* 27:1–16
123. Clark A, Daniels R (2004) Modeling the effect of physiogeographic region on wood properties of planted loblolly pine in the Southern United States. In: Connection between forest resource and wood quality: modeling approaches and simulation software. Fourth Workshop of the IUFRO Working Party S5.01-04, 8–15 September 2002, INRA-Centre de Recherches de Nancy, France, Harrison Hot Springs, British Columbia, Canada, pp 54–60
124. Samuelson LJ, Butnor J, Maier C, Stokes TA, Johnsen K, Kane M (2008) Growth and physiology of loblolly pine in response to long-term intensive management: defining growth potential in the southeastern United States. *Can J For Res* 38:721–732
125. Allen HL, Fox TR, Campbell RG (2005) What is ahead for intensive pine plantation silviculture in the South? *South J Appl For* 29: 62–69
126. Borders BE, Bailey RL (2001) Loblolly pine—pushing the limits of growth. *South J Appl For* 25:69–74
127. Albaugh TJ, Allen HL, Dougherty PM, Johnsen KH (2004) Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *For Ecol Manag* 192:3–19
128. Burkes EC, Will RE, Barron-Gafford GA, Teskey RO, Shiver B (2003) Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. *For Sci* 49:224–234
129. Adegbidi HG, Jokela EJ, Comerford NB, Barros NF (2002) Biomass development of intensively managed loblolly pine plantations growing on Spodosols in the southeastern USA. *For Ecol Manag* 167:91–102
130. Lorentz KA, Minogue PJ (2014) Exotic *Eucalyptus* plantations in the southeastern US: risk assessment, management and policy approaches. *Biol Invasions* 17:1581–93
131. Callahan MA, Stanturf JA, Hammond WJ, Rockwood DL, Wenk ES, O'Brien JJ (2013) Survey to evaluate escape of *Eucalyptus* spp. seedlings from plantations in southeastern USA. *Int J For Res* (Article ID 946374, 10 pp). doi:10.1155/2013/946374
132. Goodrick SL, Stanturf JA (2012) Evaluating potential changes in fire risk from *Eucalyptus* plantings in the Southern United States. *Int J For Res* (article ID 680246, 9 pp). doi:10.1155/2012/680246
133. Headlee WL, Hall RB, Zalesny RS Jr, Langholtz MH (2014) Comparing poplars to eucalypts and loblolly pine on marginal lands in the southeastern USA—preliminary results from a project modeling biomass productivity and economic performance. In: International Poplar Symposium VI, 20–23 July 2014, Vancouver, British Columbia, Canada
134. Headlee W, Hall R, Zalesny RS Jr, Langholtz M (2015) Optimizing woody biomass management and economics in the southeastern USA. In: Proceedings of USDA NIFA Fellowship Project Directors' Meeting, 4–5 August 2015, Washington, DC, pp 31–32
135. Hansen EA (1991) Poplar woody biomass yields: a look to the future. *Biomass Bioenergy* 1:1–7
136. Zhu JY, Pan X, Zalesny RS Jr (2010) Pretreatment of woody biomass for biofuel production: energy efficiency, technologies, and recalcitrance. *Appl Microbiol Biotechnol* 87:847–857
137. Gardiner ES (2014) Outlook for Mississippi Alluvial Valley forests: a subregional report from the Southern Forest Futures Project. Gen Tech Rep SRS-201. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 83 pp
138. Stanturf JA, Portwood CJ (1999) Economics of afforestation with eastern cottonwood (*Populus deltoides*) on agricultural land in the Lower Mississippi Alluvial Valley. Tenth Biennial Southern Silvicultural Research Conference, 18–19 February 1999, Shreveport, LA, pp 66–72
139. Byrd A, Hood WG, Tyree MC, Dillaway DN (2015) Estimation of above ground biomass for multi-stemmed short-rotation woody crops. In: Gordon HA, Connor KF, Haywood JD (eds) Proceedings of the 17th Biennial Southern Silvicultural Research Conference. e-Gen Tech Rep SRS-203. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 313–314, (551 pp)
140. Perlack RD, Wright LL, Turhollow AF, Graham RF, Stokes BJ, Erbach DC (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. DOE/GO-102005-2135. Prepared by Oak Ridge National Laboratory for US Department of Energy and US Department of Agriculture. [http://feedstockreview.ornl.gov/pdf/billion\\_ton\\_vision.pdf](http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf)

141. US Department of Agriculture, Forest Service (2008) Woody biomass utilization strategy. Patton-Mallory M (ed). US Department of Agriculture, Forest Service, Washington Office, Washington, DC, 17 pp
142. US Department of Agriculture, Forest Service (2011) The Forest Service Strategic Energy Framework. US Department of Agriculture, Forest Service, Office of the Deputy Chief, National Forest System, Washington, DC, 22 pp
143. Perlack RD, Ranney JW, Wright LL (1992) Environmental emissions and socioeconomic considerations in the production, storage, and transportation of biomass energy feedstocks. Final Report for US Department of Energy. Oak Ridge National Laboratory, Oak Ridge, TN
144. Elbehri A (2007) The changing face of the U.S. grain system: differentiation and identity preservation trends. Econ Res Report 35. US Department of Agriculture, Economic Research Service, Washington, DC, 32 pp
145. Benjamin JG, Lilieholm RJ, Coup CE (2010) Forest biomass harvesting in the Northeast: a special-needs operation. North J Appl For 27:45–49
146. Altman I, Johnson T (2008) The choice of organizational form as a non-technical barrier to agro-bioenergy industry development. Biomass Bioenergy 32:28–34
147. Dasmohapatra S (2009) Future market drivers for the forest products industry. Bioresources 4:1263–1266
148. Gronowska M, Joshi S, MacLean HL (2009) A review of U.S. and Canadian biomass supply studies. Bioresources 4:341–369
149. Berwick M, Farooq M (2003) Truck costing model for transportation managers. Upper Great Plains Transportation Institute, North Dakota State University, Fargo, ND, 53 pp
150. Young TM, Hodges DG, Abt RC, Hartsell AJ, Perdue JH (2009a) Regional comparative advantage for woody biofuels production. Final Report for US Department of Transportation and Southeastern SunGrant Center submitted by The University of Tennessee, Knoxville, TN, 167 pp
151. Young TM, Perdue JH, Hartsell A, Abt RC, Hodges DG, Rials TG (2009b) A real-time web-based optimal Biomass Site Assessment Tool (BioSAT): module 1. An economic assessment of mill residues for the Southern U.S. In: McWilliams W, Moisen G, Czaplewski R (comps) Forest Inventory and Analysis (FIA) Symposium 2008, 21–23 October 2008, Park City, UT. Proc RMRS-P-56CD. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 22 pp
152. Perdue JH, Young TM, Rials TG (2011) The Biomass Site Assessment Model—BioSAT. Final Report for US Department of Agriculture, Forest Service, Southern Research Station submitted by The University of Tennessee, Knoxville, TN, 282 pp
153. Young TM, Zaretzki RL, Perdue JH, Guess FM, Liu X (2011) Logistic regression models of factors influencing the location of bioenergy and biofuels plants. BioResources 6:329–343
154. Jackson SW, Rials T, Taylor A, Bozell J, Norris K (2010) Wood 2 Energy: A State of the Science and Technology Report (PDF). Accessed 11 January 2016. <http://www.wood2energy.org>
155. Aguilar FX, Saunders A (2010) Policy instruments promoting wood for energy uses: evidence from the continental U.S. J For 108:132–140
156. Perez-Verdin G, Grebner DL, Sun C, Munn IA, Schultz EB, Matney TG (2009) Woody biomass availability for bioethanol conversion in Mississippi. Biomass Bioenergy 33:492–503
157. Openshaw K (2010) Biomass energy: employment generation and its contribution to poverty alleviation. Biomass Bioenergy 34: 365–378
158. Young TM, Perdue JH, Hartsell AJ, Rials TG (2011b) An economic assessment for biomass in the Southern U.S. using the Biomass Site Assessment Tool (BioSAT). In: Shelly JR (ed) Woody biomass utilization: Proceedings of the International Conference on Woody Biomass Utilization, 4–5 August 2009, Starkville, MS. Forest Products Society, Madison, WI, pp 93–107
159. Huang X, Perdue JH, Young TM (2012) A spatial index for identifying opportunity zones for woody cellulosic conversion facilities. Int J For Res (article ID 106474, 11 pp). doi:10.1155/2012/106474
160. Hinchey M, Rottmann W, Mullinax L, Zhang C, Chang S, Cunningham M, Pearson L, Nehra N (2009) Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cell Dev Biol - Plant 45:619–629
161. Perdue JH, Stanturf JA, Young TM, Huang X, Dougherty (2013) An economic geospatial analysis of short-rotation woody crops. Final Report for US Department of Agriculture, Forest Service, Southern Research Station submitted by The University of Tennessee, Knoxville, TN, 130 pp
162. Young TM, Han LD, Guess FM, Hargrove SR, Huang X, Perdue JH, Chen CH (2014) Modeling the impact of the emerging bioeconomy on transportation network flows with simulation and Bayesian inference. Final Report for US Department of Transportation and Southeastern SunGrant Center submitted by The University of Tennessee, Knoxville, TN, 69 pp
163. Stanturf JA, Gardiner ES, Hamel PB, Devall MS, Leininger TD, Warren ME Jr (2000) Restoring bottomland hardwood ecosystems in the Lower Mississippi Alluvial Valley. J For 98:10–16
164. Gardiner E, Stanturf J, Leininger T, Hamel P, Dorris L Jr, Portwood J, Shepard J (2008) Establishing a research and demonstration area initiated by managers: the Sharkey Restoration Research and Demonstration Site. J For 106:363–369
165. Van Voorhis C (2012) The rise of natural capitalism and the new frontier of the restoration economy. For Landowner (November/December), pp 18–25
166. Birdsey RA (1992) Carbon storage and accumulation in United States forest ecosystems. General Technical Report WO-59. US Department of Agriculture, Forest Service, Washington Office, Washington, DC, p 51
167. Heilman PE, Stettler RF (1985) Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. Can J For Res 15:384–388
168. Rajora OP, Zsuffa L (1990) Allozyme divergence and evolutionary relationships among *Populus deltoides*, *P. nigra*, and *P. maximowiczii*. Genome 33:44–49
169. Eckenwalder JE (1996) Systematics and evolution of *Populus*, part I, Ch. 1. In: Stettler RF, Bradshaw HD Jr, Heilman PE, Hinckley TM (eds) Biology of *Populus* and its implications for management and conservation. NRC Research Press, National Research Council of Canada, Ottawa, ON, pp 7–32
170. Schulze B, Wirth C, Linke P, Brand WA, Kuhlmann I, Horna V, Schulze ED (2004) Laser ablation–combustion–GC–IRMS: a new method for online analysis of intra-annual variation of  $\delta^{13}\text{C}$  in tree rings. Tree Physiol 24:1193–1201
171. Ripullone F, Lauteri M, Grassi G, Amato M, Borghetti M (2004) Variation in nitrogen supply changes water-use efficiency of *Pseudotsuga menziesii* and *Populus × euramericana*; a comparison of three approaches to determine water-use efficiency. Tree Physiol 24:671–679
172. Monclus R, Dreyer E, Villar M, Delmotte FM, Delay D, Petit J-M, Marron N, Bréchet C, Brignolas F (2006) Impact of drought on productivity and water use efficiency in 29 genotypes of *Populus deltoides* × *P. nigra*. New Phytol 169:765–777
173. Dillen SY, Marron N, Koch B, Ceulemans R (2008) Genetic variation of stomatal traits and carbon isotope discrimination in two hybrid poplar families (*Populus deltoides* 'S9-2' × *P. nigra* 'Ghoy' and *P. deltoides* 'S9-2' × *P. trichocarpa* 'V24'). Ann Bot 102:399–407
174. Yin C, Wang X, Duan B, Luo J, Li C (2005) Early growth, dry matter allocation and water use efficiency of two sympatric

- Populus* species as affected by water stress. Environ Exp Bot 53: 315–322
175. Dvorak WS (2012) Water use in plantations of eucalypts and pines: a discussion paper from a tree breeding perspective. Int For Rev 14:110–119
176. Ouyang Y, Xu D, Leininger TD, Zhang N (2016) A system dynamic model to estimate hydrological processes and water use in a eucalypt plantation. Ecol Eng 86:290–299
177. Vose JM, Miniati CF, Sun G, Caldwell PV (2015) Potential implications for expansion of freeze-tolerant *Eucalyptus* plantations on water resources in the Southern United States. For Sci 61:509–521
178. Zalesny RS Jr, Stanturf JA, Evett SR, Kandil NF, Soriano C (2011) Opportunities for woody crop production using treated wastewater in Egypt. I. Afforestation strategies. Int J Phytoremed 13:102–121
179. Evett SR, Zalesny RS Jr, Kandil NF, Stanturf JA, Soriano C (2011) Opportunities for woody crop production using treated wastewater in Egypt. II. Irrigation strategies. Int J Phytoremed 13:122–139
180. Moreau B, Gardiner ES, Stanturf JA, Fisher RK (2004) Estimating leaf nitrogen of eastern cottonwood trees with a chlorophyll meter. In: Connor KF (ed) Gen Tech Rep SRS-71. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, pp 487–491 (594 pp)
181. Hamel PB (2003) Winter bird community differences among methods of bottomland hardwood forest restoration: results after seven growing seasons. Forestry 76:189–197
182. Kennedy HE Jr, Krinard RM (1988) Coppice growth and development of three bottomland hardwoods through four years. In: McCaskey TA, Lockaby BG (comps) Southern Biomass Conference: A Joint Meeting of the Southern Biomass Energy Research Group and the Southern Forestry Biomass Working Group. Auburn University, Auburn, AL, pp 3–5, (62 pp)
183. Davis AA, Trettin CC (2006) Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina. Biomass Bioenergy 30:769–777
184. Tang Z, Land SB Jr (1996) Early growth, leaf development, and dry-weight production of sycamore rooted cuttings. Biomass Bioenergy 10:221–229
185. Leininger TD, Schiff NM, Corbin K (2004) *Homalodisca coagulata* transmits *Xylella fastidiosa* to sycamore. Phytopathology 94:S59
186. Chatterjee S, Wistrom C, Lindow SE (2008) A cell–cell signaling sensor is required for virulence and insect transmission of *Xylella fastidiosa*. Proc Natl Acad Sci U S A 105:2670–2675
187. Leininger TD, Britton KO, Chang CJ (1999a) Determining the role of bacterial leaf scorch, canker stain, and *Botryosphaeria* canker in the dieback of plantation sycamores in the southeastern United States. In: Ash CL (ed) Shade tree wilt diseases—Proceedings from Wilt Diseases of Shade Trees: A National Conference. APS Press, St. Paul, MN, pp 209–216, (257 pp)
188. Leininger TD, Solomon JD, Wilson AD, Schiff NM (1999b) A guide to major insects, diseases, air pollution injury, and chemical injury of sycamore. Gen Tech Rep SRS-28. US Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 44 pp
189. Amichev BY, Hangs RD, Konecni SM, Stadnyk CN, Volk TA, Bélanger N, Vujanovic V, Schoenau JJ, Moukoui J, Van Rees KCJ (2014) Willow short-rotation production systems in Canada and Northern United States: a review. Soil Sci Soc Am J 78:S168–S182
190. Maisenhelder LC (1957) Propagation of some Delta hardwoods by rooting. In: Proceedings of the 4th Southern Forest Tree Improvement Conference, pp 55–58 (147 pp)
191. Randall WK (1971) Willow clones differ in susceptibility to cottonwood leaf beetle. In: Proceedings of the 11th Southern Forest Tree Improvement Conference, Southern Forest Tree Improvement Committee Sponsored Publication 33, Macon, GA, pp 108–111 (229 pp)
192. Kumpulainen S (2006) Vulnerability concepts in hazard and risk assessment. Geol Surv Finland (Special Paper) 42:65–74
193. Wisner B, Blaikie P, Cannon T, Davis I (2003) At risk: natural hazards, people's vulnerability, and disasters. Routledge, London, 496 pp